Cosmological Simulations with SIDM

Miguel Rocha - UC Irvine

TAUP 2013
Asilomar 09/10/2013

In Collaboration With

Annika Peter

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Manoj Kaplinghat

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Jose Onorbe

Summary of Controversies with the Standard Model of Structure Formation

- **Cusp-core problem**: persists in isolated galaxies. Supernova feedback may explain this in LCDM

- **Too big to fail**: evident in dSphs of MW and M31 (makes "unlucky" Milky Way less likely explanation). May be explained in LCDM if SN feedback is very efficient and most dwarfs have been orbiting for a long time and MW mass is low.

- **Cores in MW satellites**: controversial at this point; imperative to get additional data. LCDM may explain this for the most massive satellites

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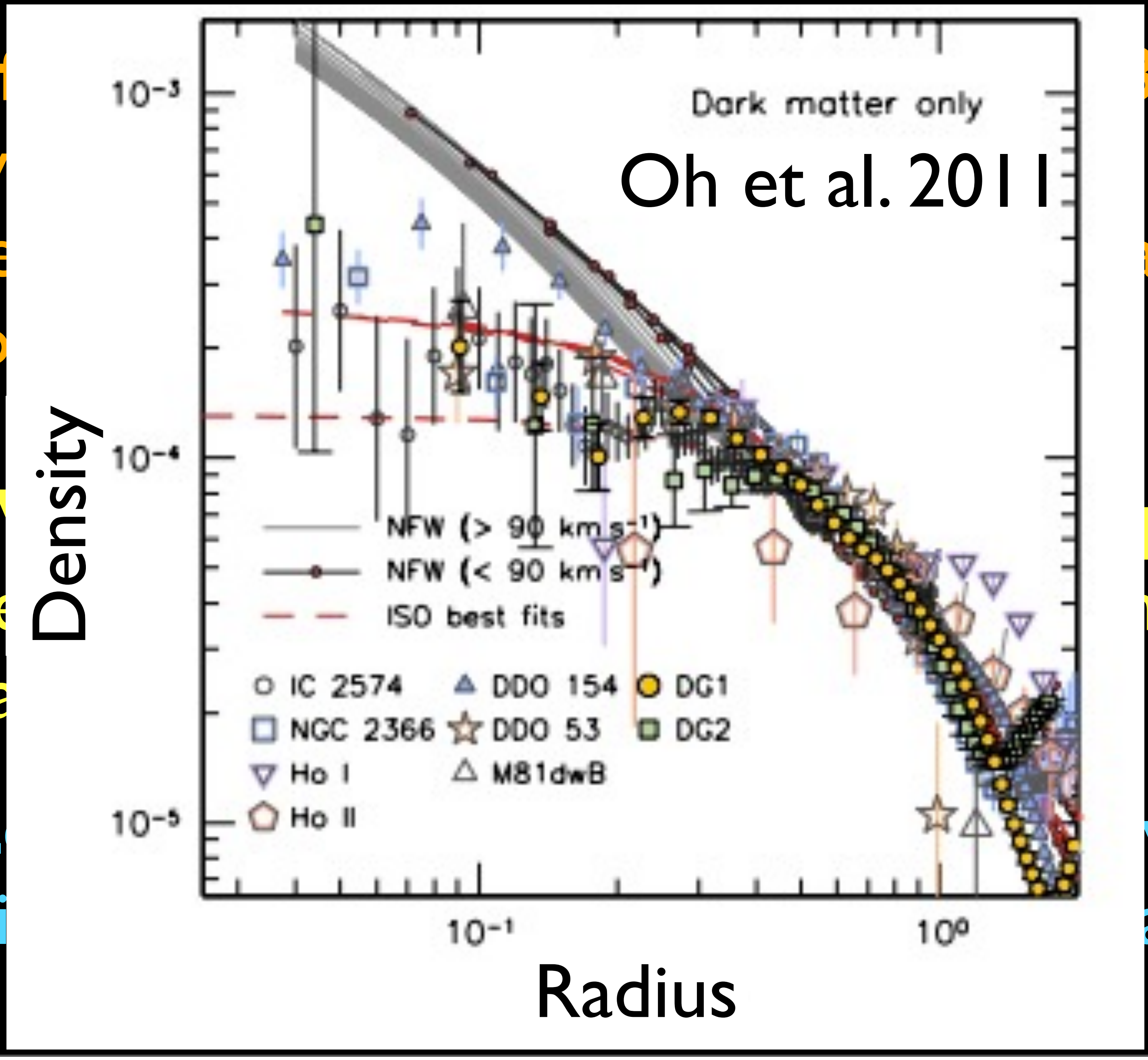

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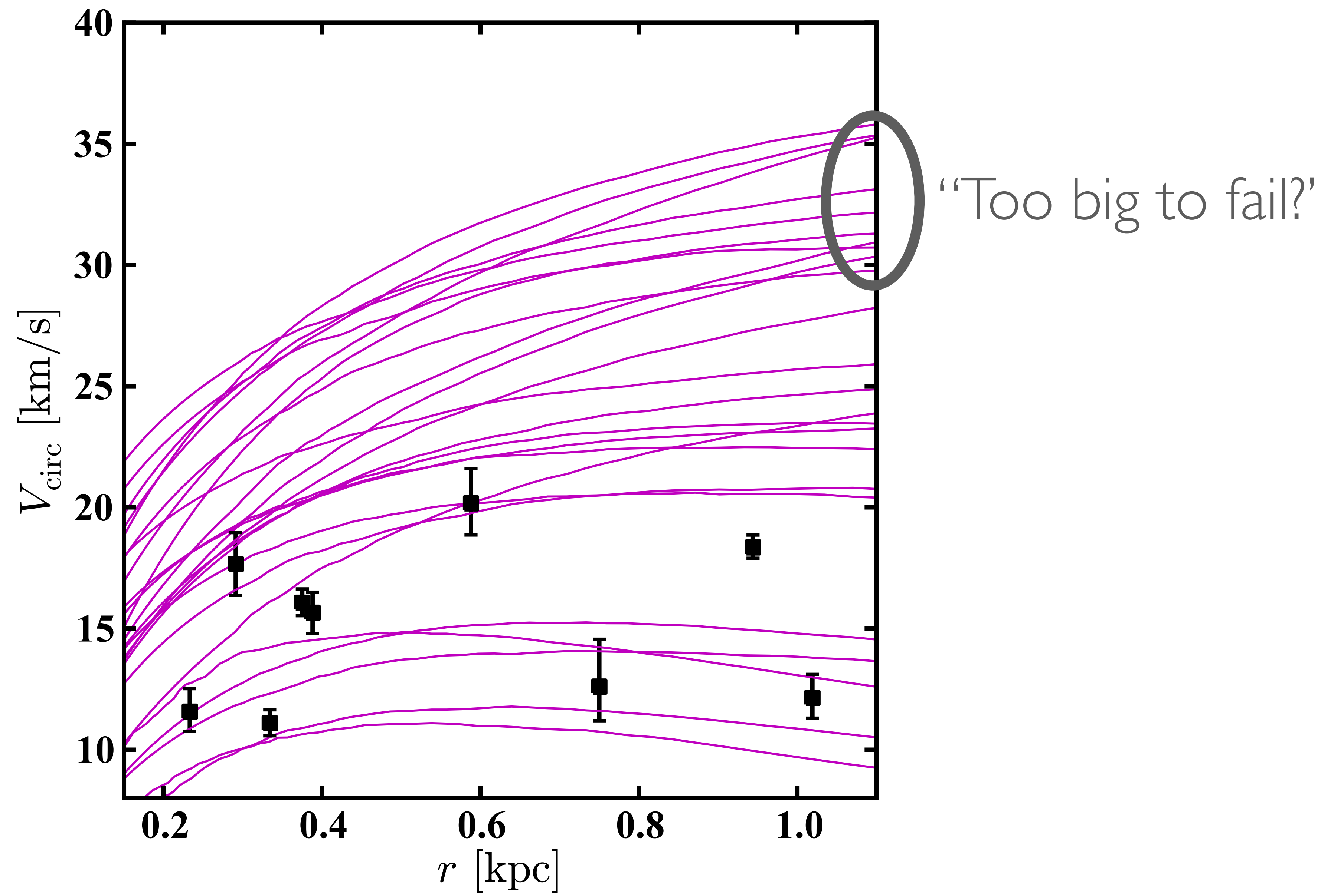

MBK, Bullock, & Kaplinghat 2011, 2012

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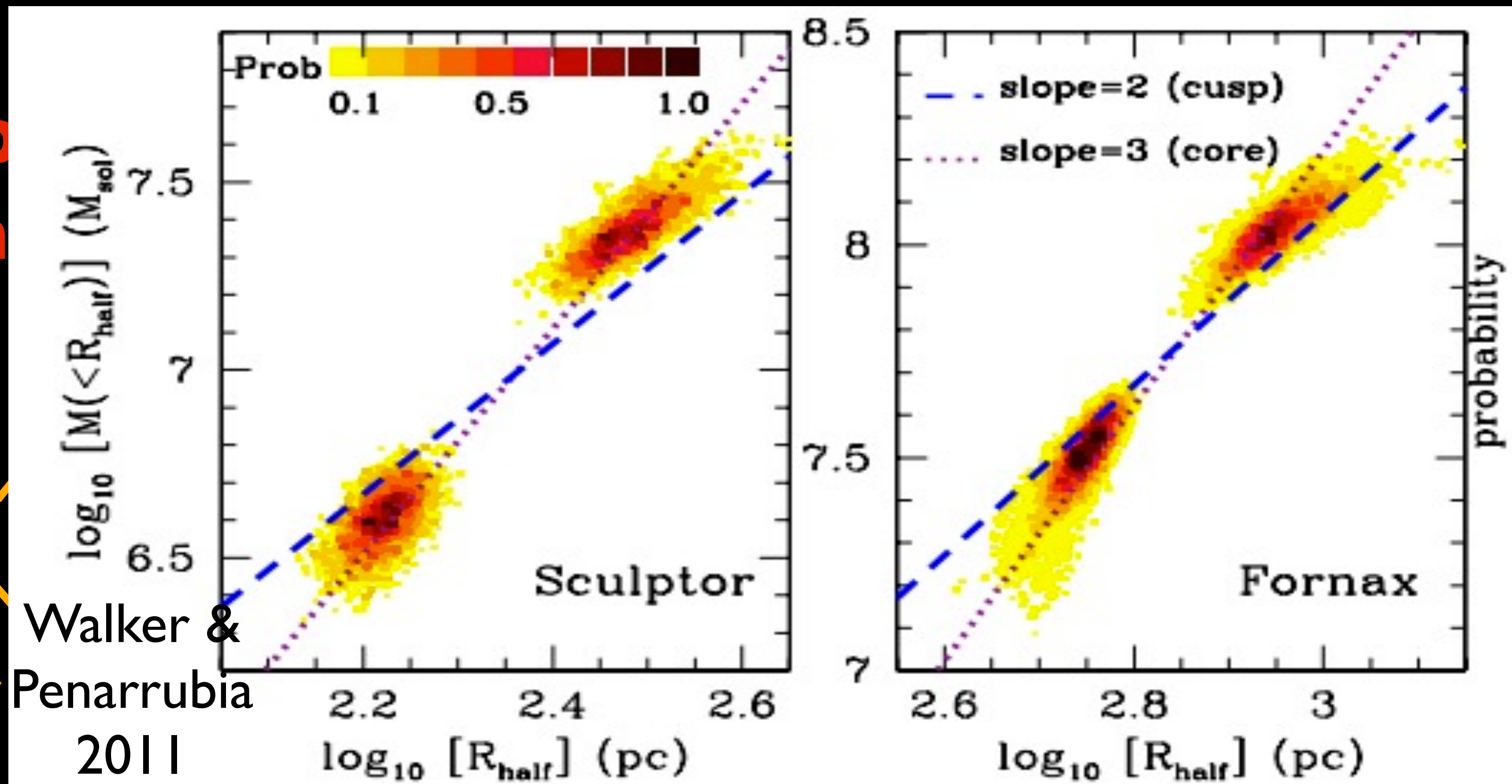

Walker & Penarrubia 2011

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~25 MW Dwarf

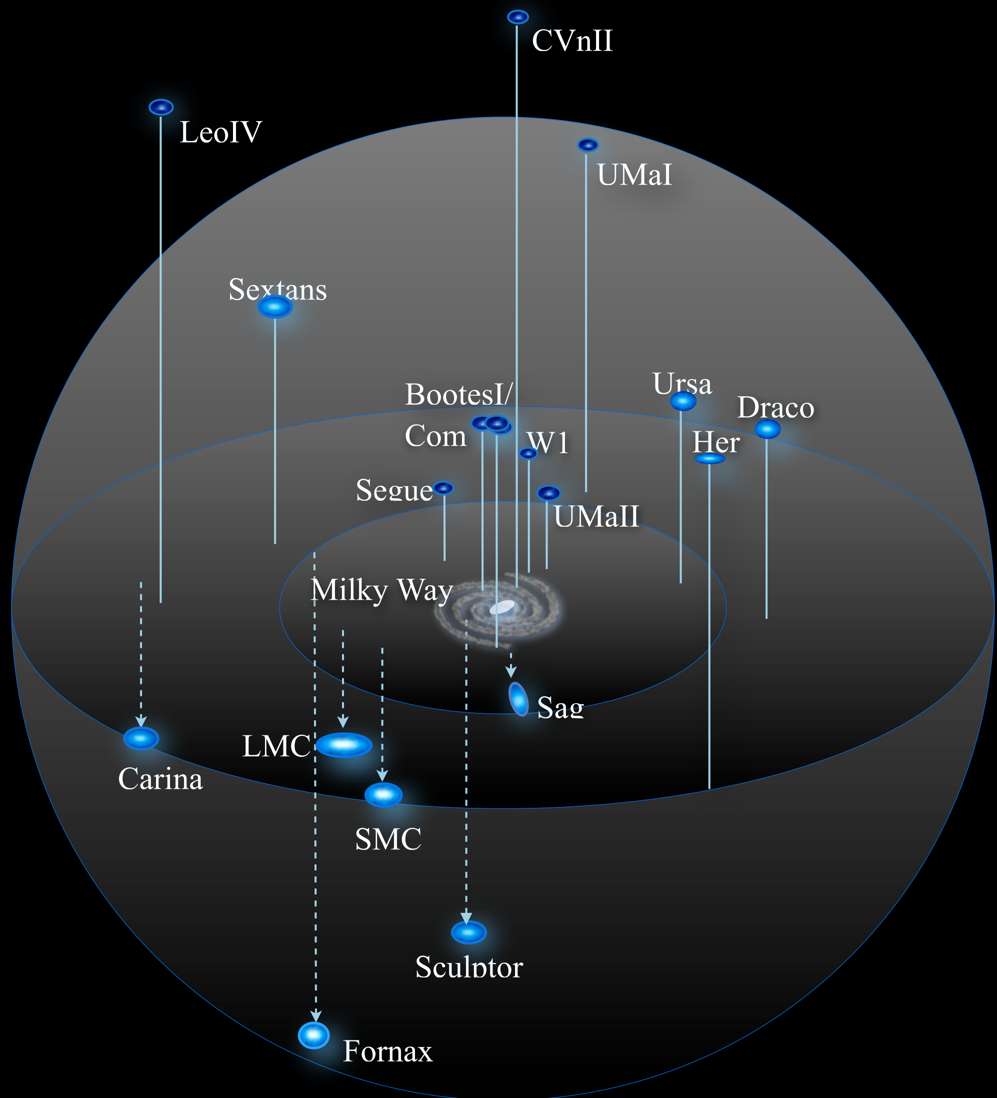

Image courtesy of James Bullock

Stadel et al. 2009

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Suggest less DM in the central regions of halos

The SIDM model

$$\Lambda\mathrm{CDM} \; + \; \frac{\sigma}{m} \neq 0$$

The SIDM model

ΛCDM $+ \quad \dfrac{\sigma}{m} \neq 0$

Interesting phenomenology if

$$\frac{\sigma}{m} = 0.1 - 100\ \mathrm{cm}^2/\mathrm{g}$$

Spergerl & Steinhardt 2000

The SIDM model

$$\Lambda\text{CDM} + \frac{\sigma}{m} \neq 0$$

Interesting phenomenology if

σ/m =1 cm²/g = 2 barn/Gev = neutron-proton scattering

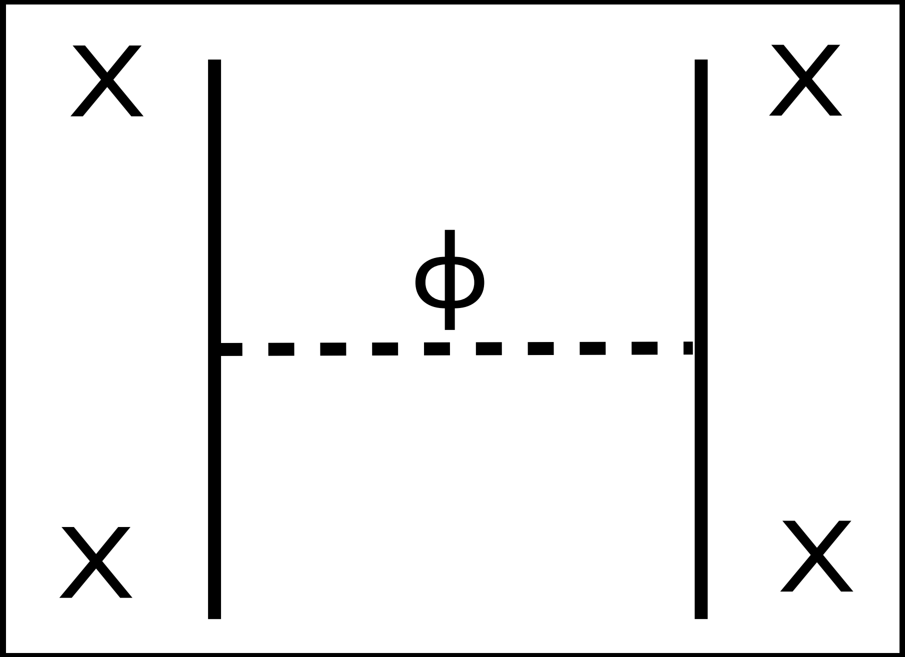
Spergerl & Steinhardt 2000

Is this a crazy idea?

Self-Interactions are a generic consequence of many models beyond the Standard Model

Just add a new force at the ~sub-Gev scale

$m_\phi = O(\mathrm{Mev})$



If your prejudice is that new physics can only be at *O*(TeV), then this large cross-sections will seem crazy

Is this a crazy idea?

Self-Interactions are a generic consequence of many models beyond the Standard Model

Examples:

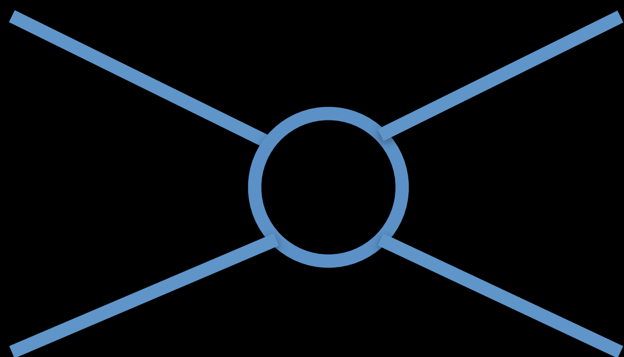
Asymmetric DM - Nussinov (1985);Kaplan (1992);Kaplan,Luty, Zurek (2009); Shelton, Zurek (2011); Buckley, Randall (2011); Morrissey, Sigurdson, Tulin (2010); Buckley (2011); Lin, Hai-Bo Yu, Zurek (2011).

Hidden Charge DM - Feng, Tu, Hai-Bo Yu (2008); Ackerman, Buckley, Carroll, Kamionkowski (2008);Feng, Kaplinghat, Tu, HBY (2009).

Atomic DM - Foot (2003); Kaplan, Krnjaic, Rehermann, Wells (2009);Feng, Kaplinghat, Tu, Hai-Bo Yu (2009);Cline, Liu, Wei Xue (2012);Francis-Yan Cyr-Racine,Kris Sigurdson (2013).

Double Disk DM - Fan, Katz, Randall, Reece (2013); McCullough,Randall (2013)

Phenomenology of DM Self-Interactions



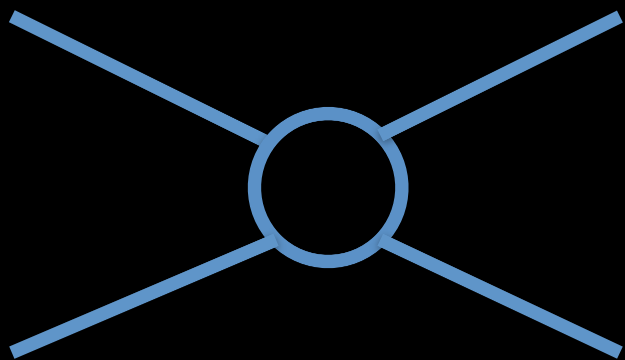
Spergerl & Steinhardt 2000

$$\xrightarrow{\hspace{4cm}}$$

Elastic - Velocity Independent - Isotropic

$$\Gamma \sim \rho \left(\frac{\sigma}{m} \right) v_{rel}$$

Phenomenology of DM Self-Interactions



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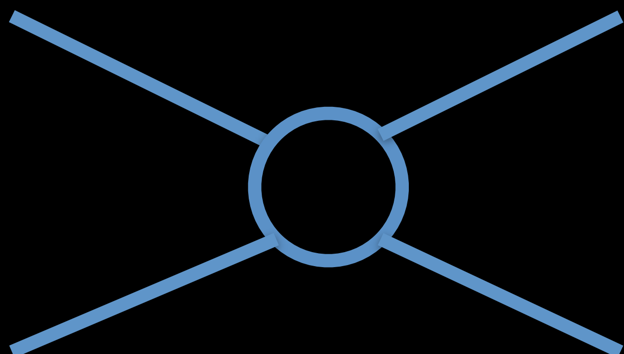
$$\Gamma \sim \rho \left(\frac{\sigma}{m} \right) v_{rel}$$

Elastic - Velocity Independent - Isotropic

Where $\Gamma / H_0 \gtrsim 1$ (central regions of DM halos)

Phenomenology of DM Self-Interactions



Spergerl & Steinhardt 2000

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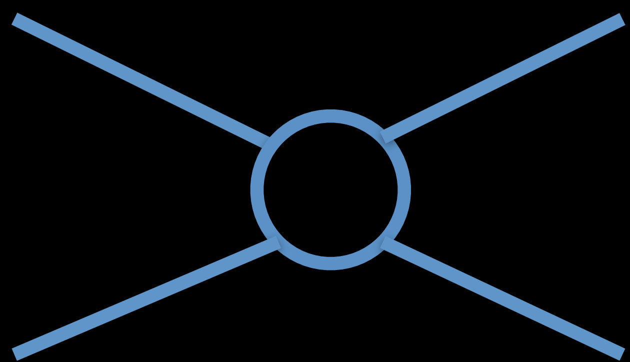
Where $\Gamma / H_0 \gtrsim 1$ (central regions of DM halos)

- The energy transfer results in isothermal low density cores

Phenomenology of DM Self-Interactions



Spergerl & Steinhardt 2000

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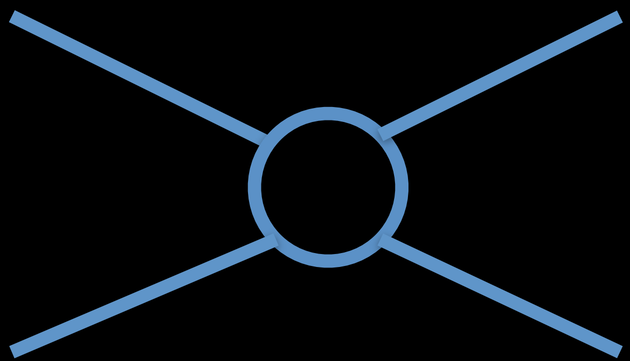
Phenomenology of DM Self-Interactions



Spergerl & Steinhardt 2000 $\longrightarrow$ $\Gamma \sim \rho \left(\frac{\sigma}{m} \right) v_{rel}$

Elastic - Velocity Independent - Isotropic

Where $\Gamma / H_0 \gtrsim 1$ (central regions of DM halos)

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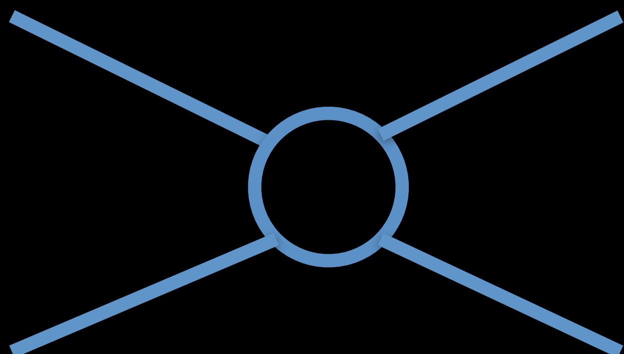
- The hot dense medium results in substructure evaporation

Phenomenology of DM Self-Interactions



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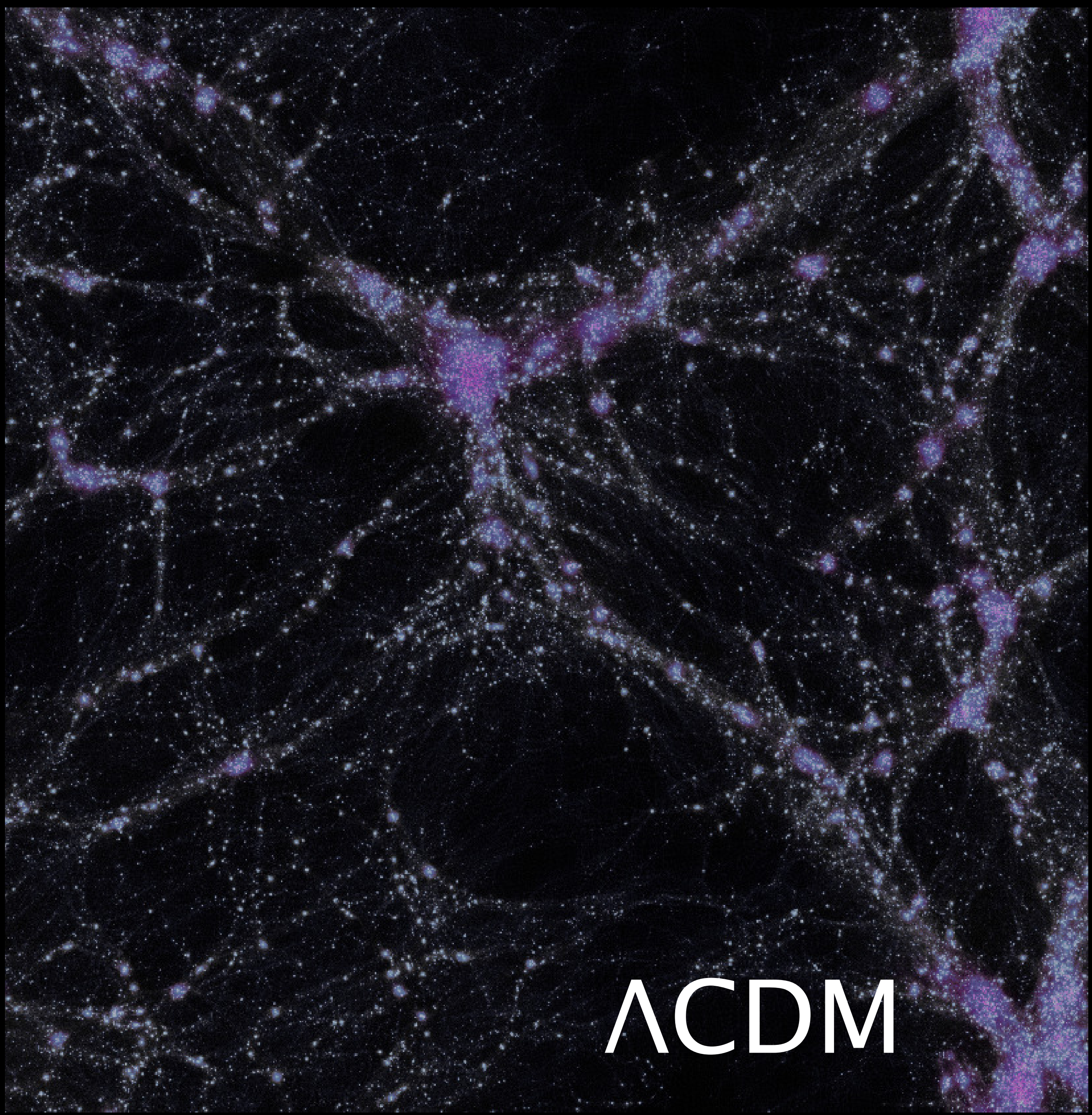
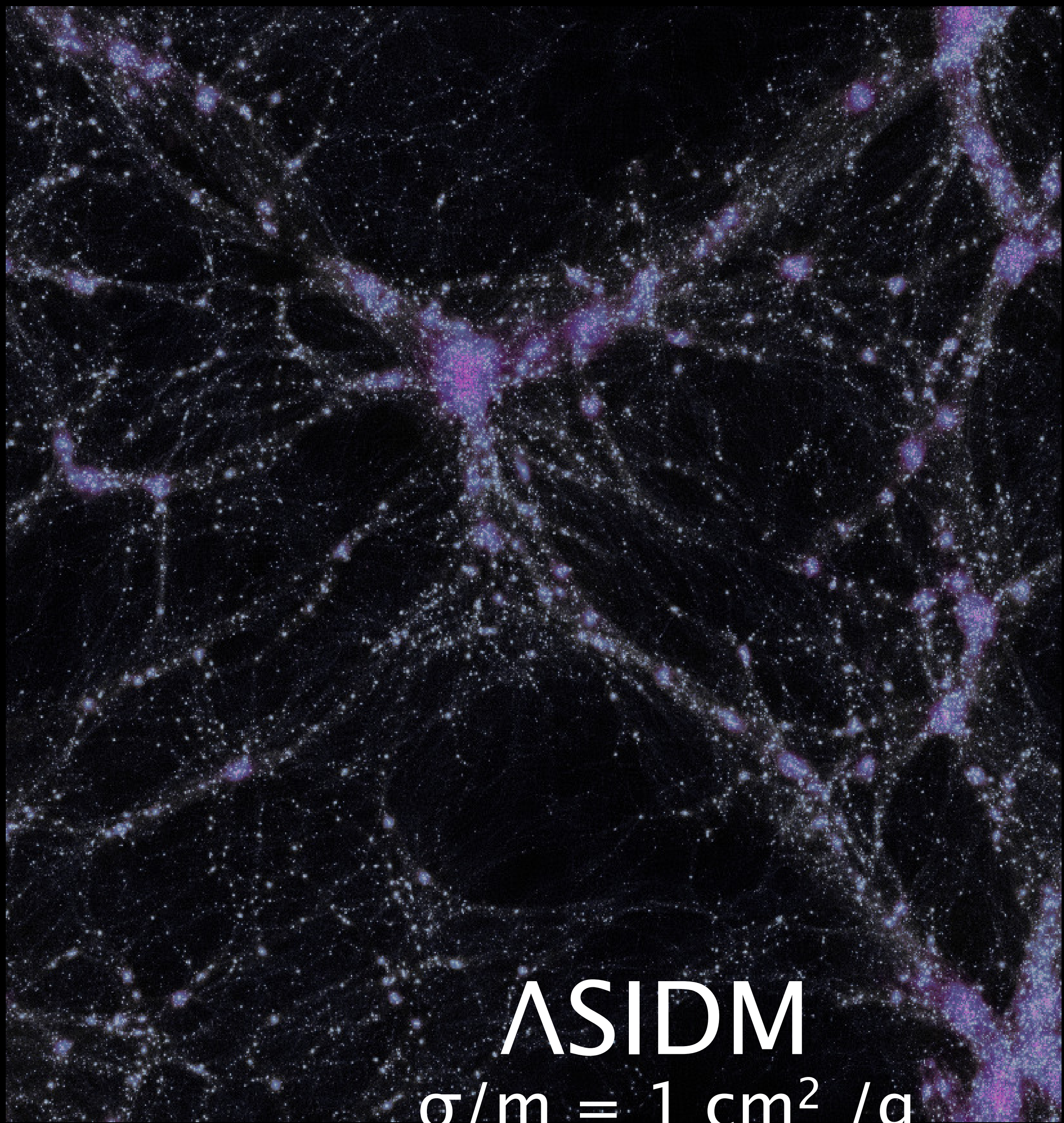
- The energy transfer results in isothermal low density cores
- The isotropic scattering produces near-spherical cores
- The hot dense medium results in substructure evaporation
- In merging systems the drag that the DM experiences would be different to that of the collisionless galaxies, resulting in an offset between the surface mass centroids and the galaxy centroids + lower M/L ratios

Results from cosmological simulations - Halo densities, shapes & substructure

Identical large-scale structure



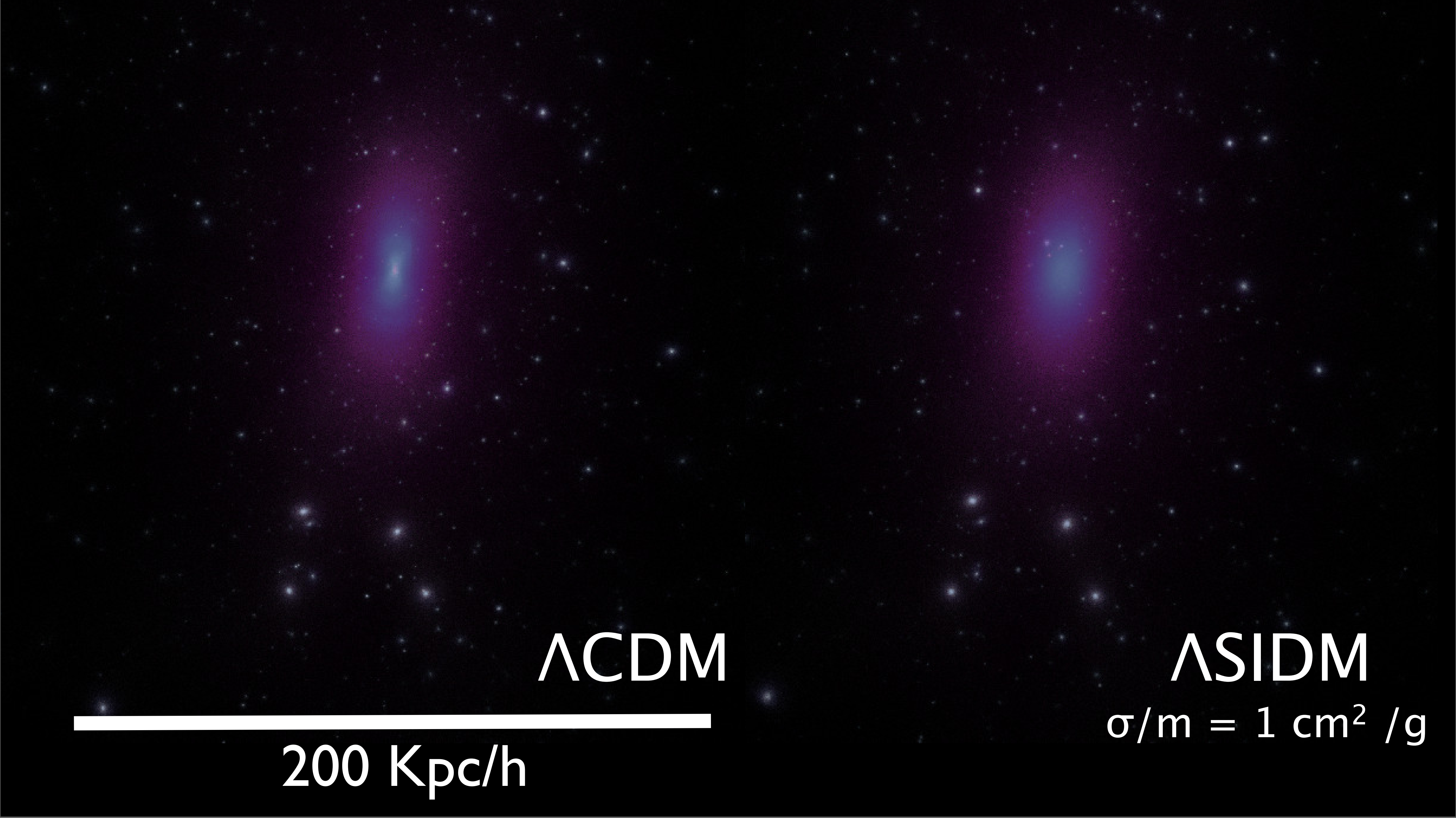


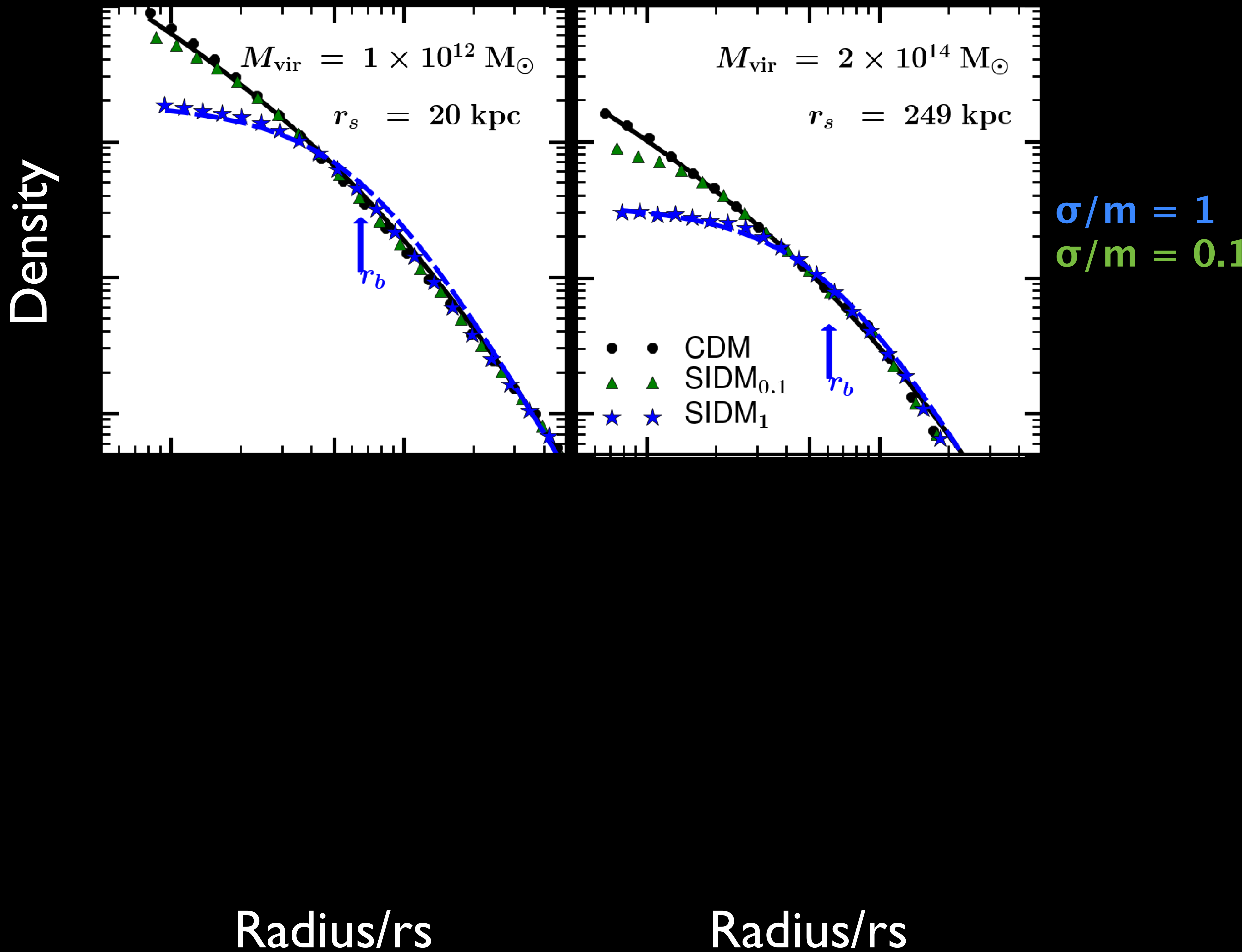
$\sigma/m = 1\ \mathrm{cm}^2\ /\mathrm{g}$

50 Mpc/h

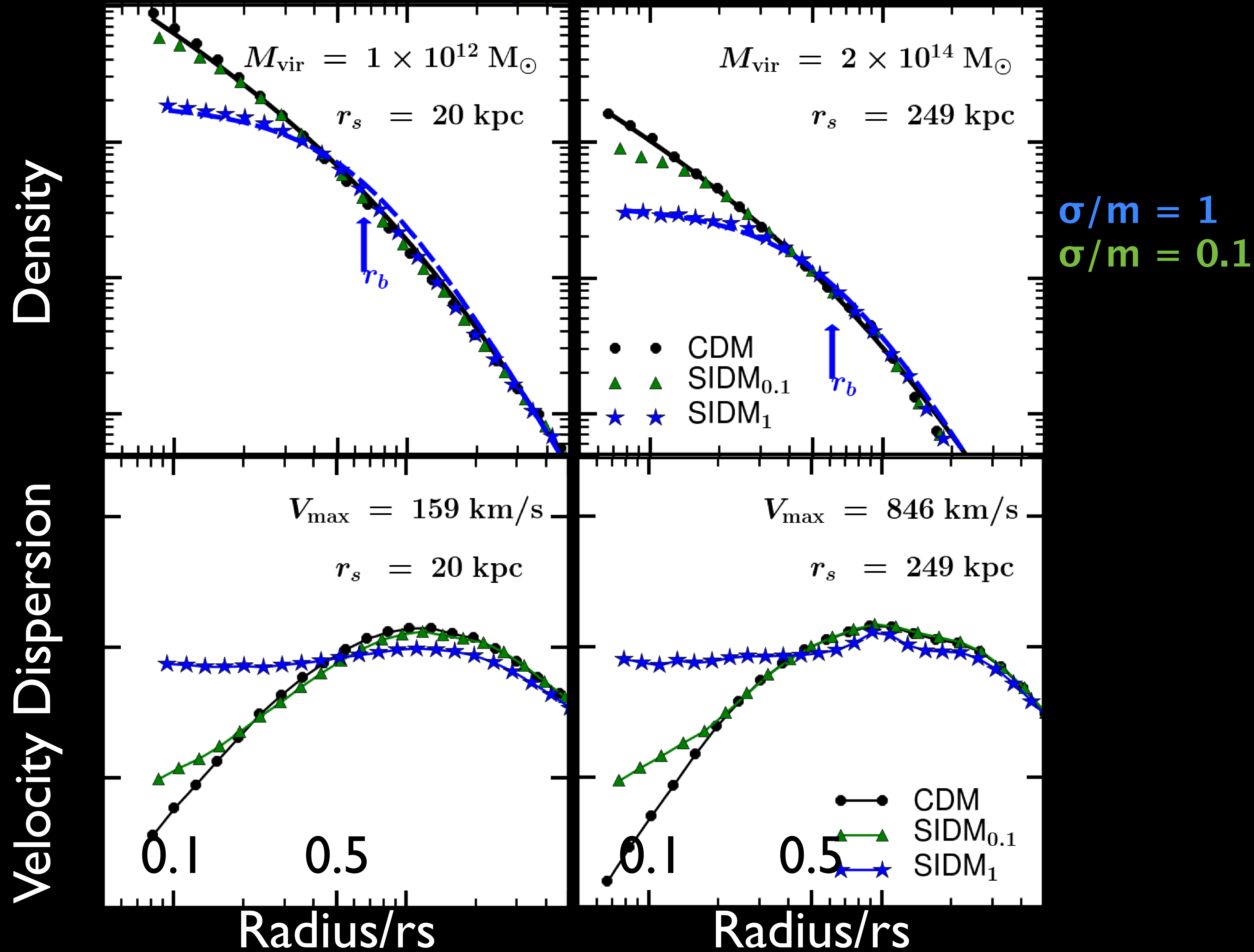
Results from cosmological simulations - Halo densities, shapes & substructure

Lower central phase-space density in SIDM halos





Density
$M_{vir} = 1 \times 10^{12}\ M_\odot$
$r_s = 20$ kpc
r_b
$M_{vir} = 2 \times 10^{14}\ M_\odot$
$r_s = 249$ kpc
CDM
$SIDM_{0.1}$
$SIDM_1$
r_b
σ/m = 1
σ/m = 0.1
Radius/rs
Radius/rs



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$V_{max} = 846$ km/s
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CDM
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$SIDM_1$
0.1
0.5
0.1
0.5
Radius/rs
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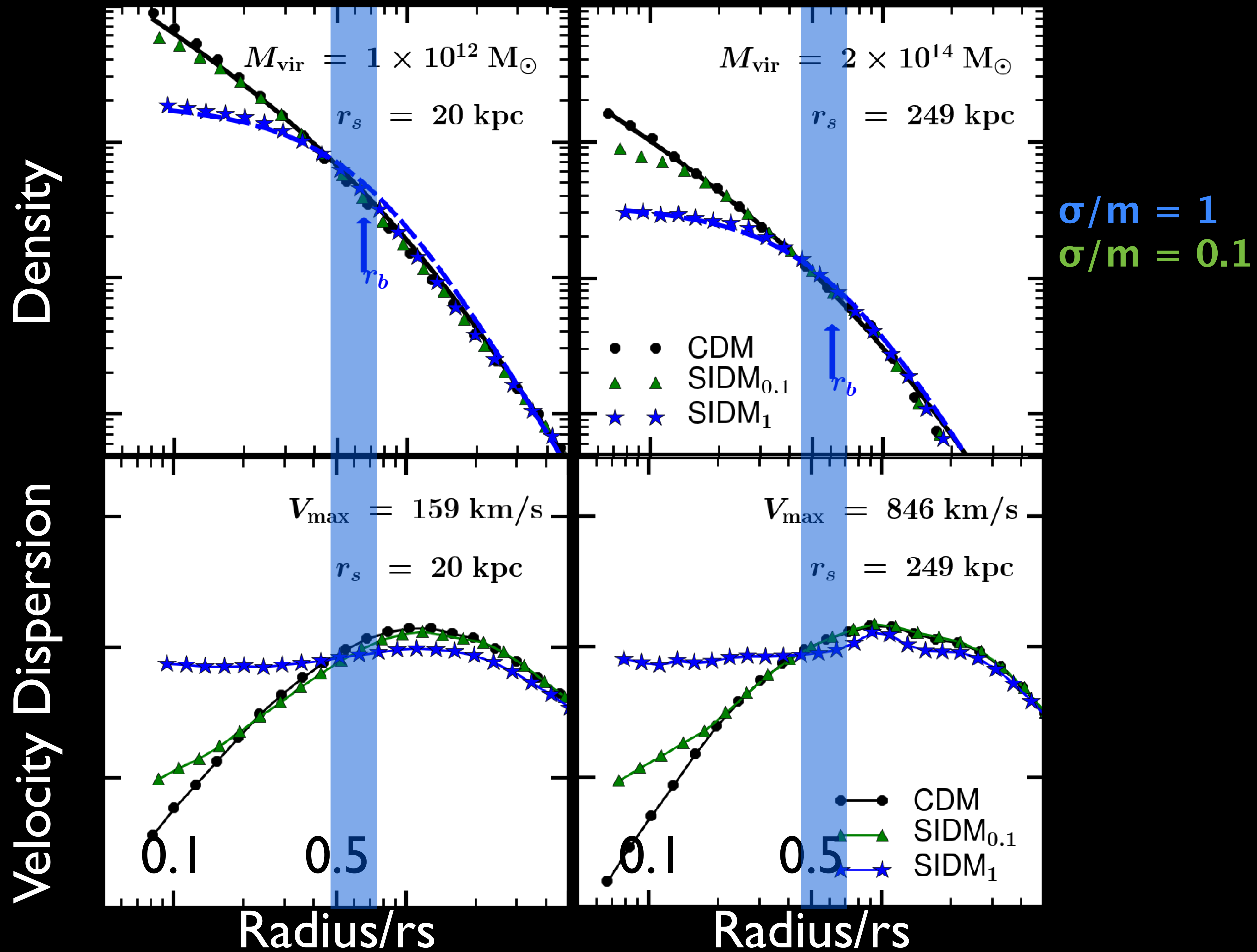

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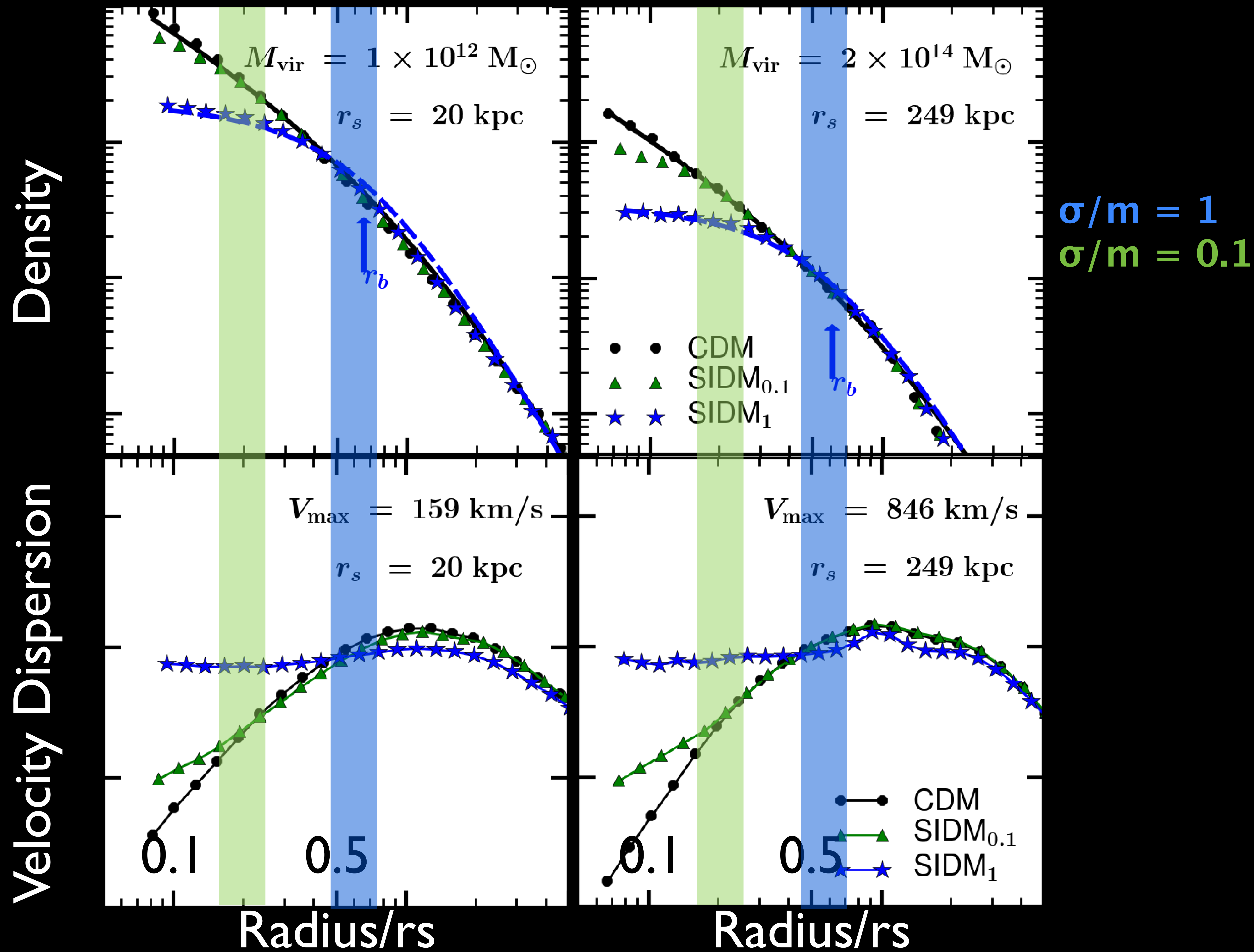

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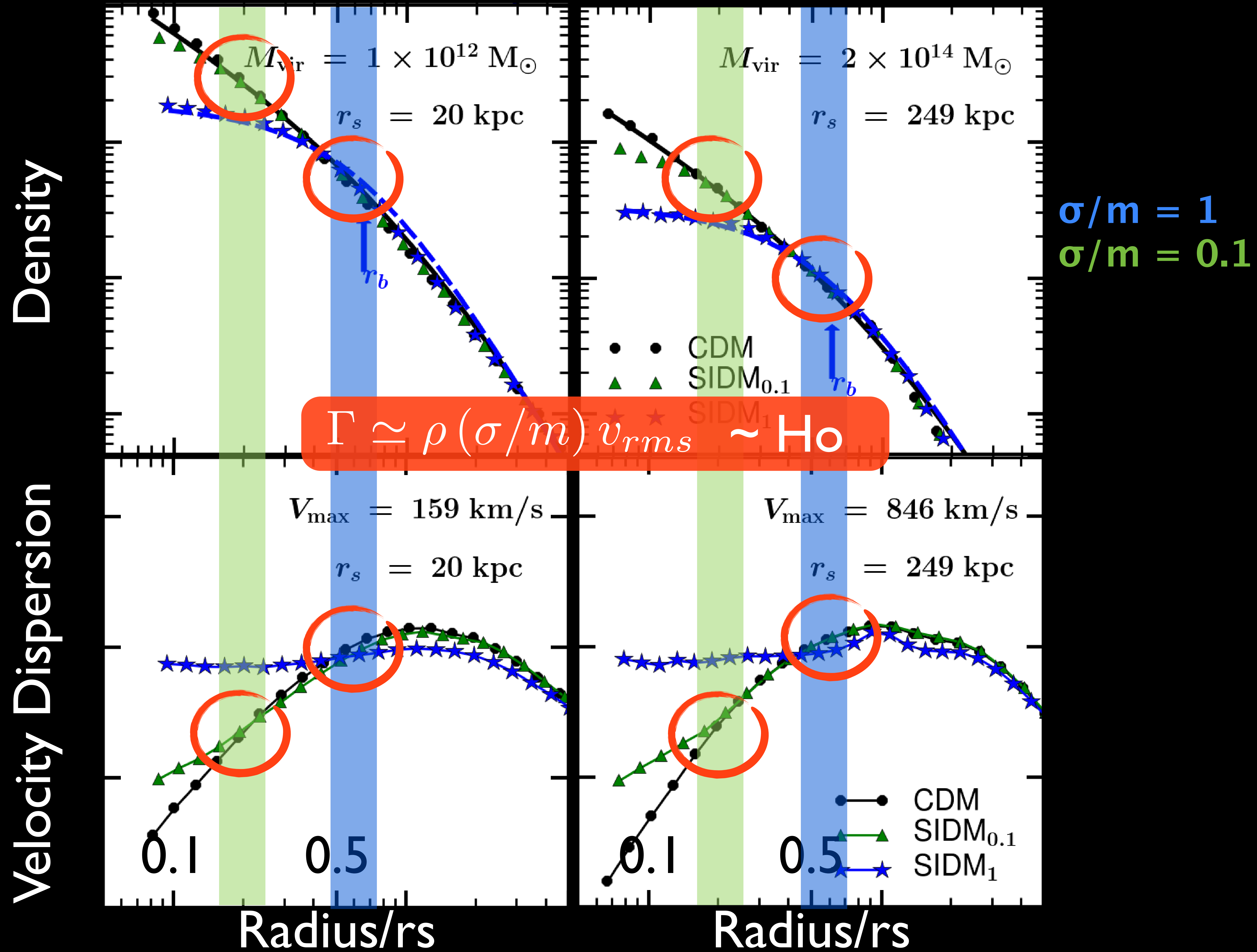
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CDM
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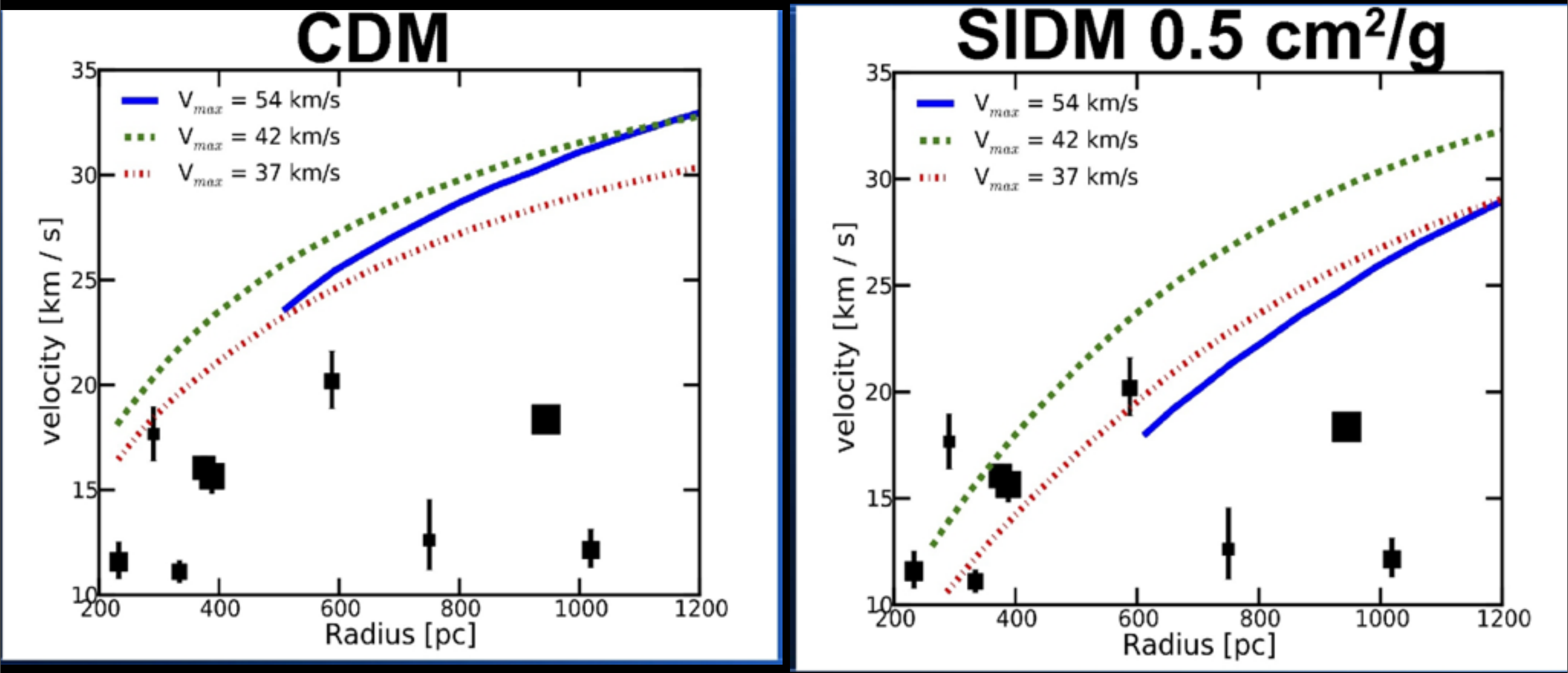
Radius/rs
Radius/rs

Results from cosmological simulations - Halo densities

	Observed	$\sigma/m = 1\ cm^2/g$	$\sigma/m = 0.1\text{–}0.5\ cm^2/g$ ✓
Clusters 700-1000 km/s	0.06-0.025 [M_{sun}/pc^3] Arabadjis et al. 2002, Sand et al. 2004, 2008, Saha et al 2006, Saha & Read 2009 Newman et al. 2009,2011	~0.005-0.004 [M_{sun}/pc^3]	~0.04 [M_{sun}/pc^3]
Low-Mass Spirals 50-130 km/s	0.5-0.01 [M_{sun}/pc^3] de Blok et al. 2001, Simon et al. 2005, Sanchez-Salcedo 2005, Kuzio de Naray et al. 2008,2010, Oh et al . 2011, Salucci et al. 2012	~0.02-0.01 [M_{sun}/pc^3]	~0.2-0.1 [M_{sun}/pc^3]
MW dSphs 20-50 km/s	~0.1 [M_{sun}/pc^3] Strigari et al. 2008, Wolf et al. 2010, Walker & Penarrubia 2011, Amorisco & Evans 2012, Wolf & Bullock 2012	~0.04-0.02 [M_{sun}/pc^3]	~0.5-0.2 [M_{sun}/pc^3]

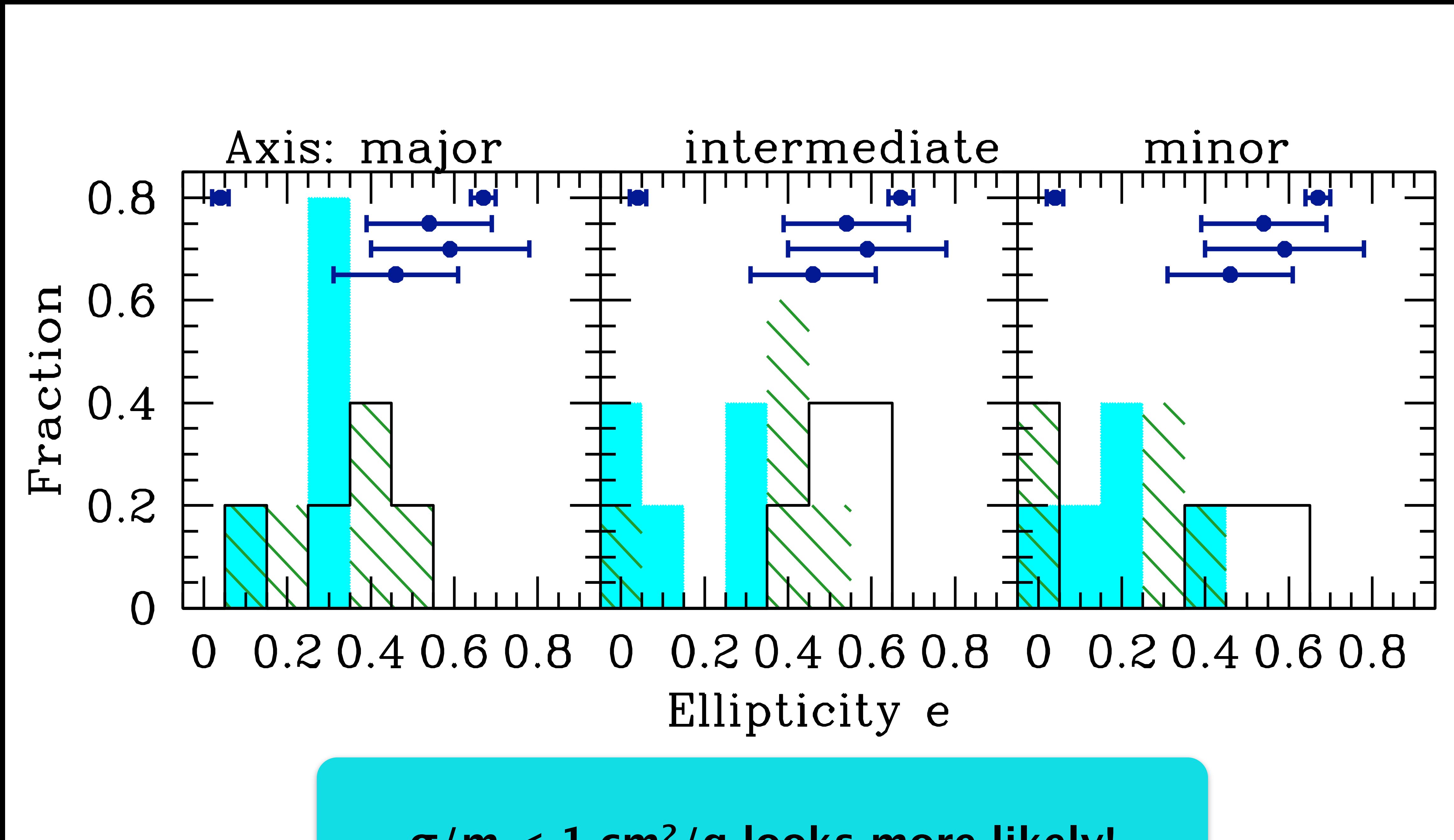
Rocha et al. 2013
Peter et al. 2013

Work in progress - Dwarfs



Oliver Elbert et al in prep.

Results from cosmological simulations - Halo shapes

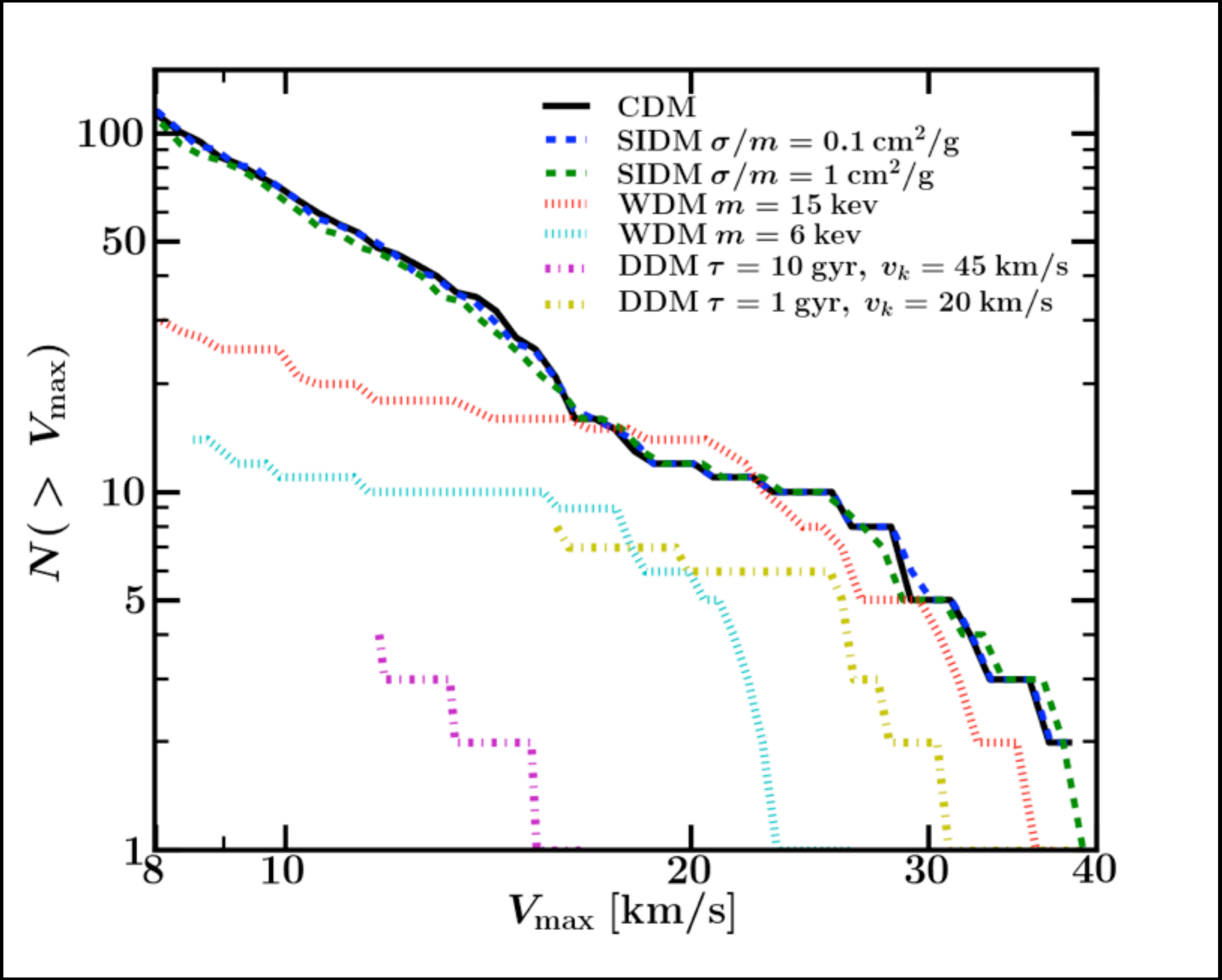


σ/m < 1 cm²/g looks more likely!

This is more than an order of magnitude less stringent than Miralda-Escude (2002), the reason is that:

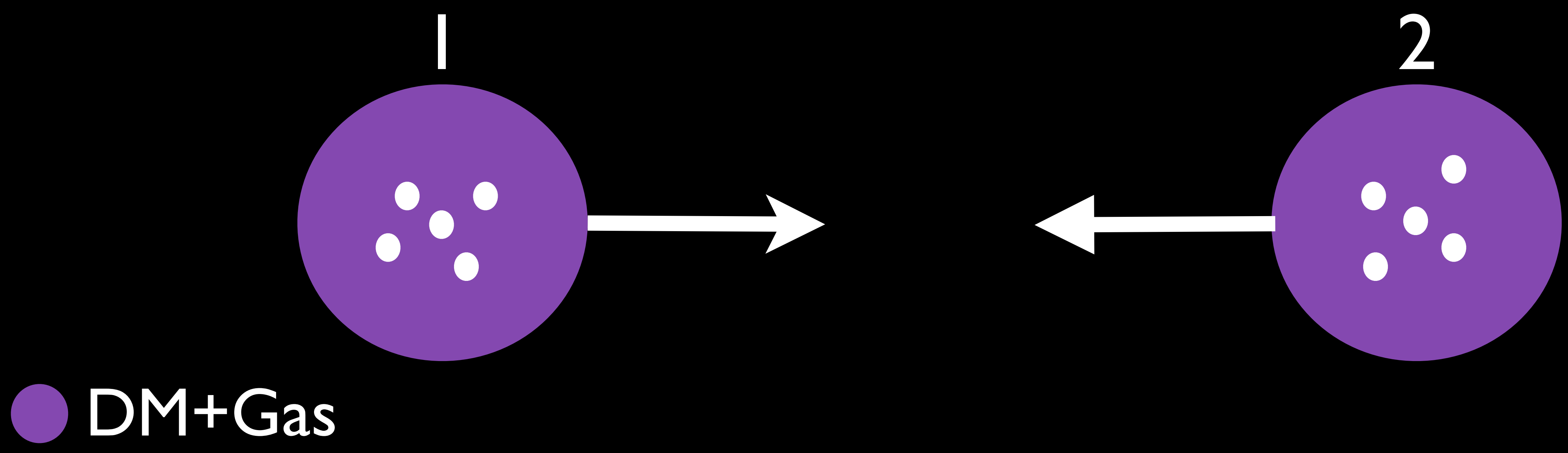
- Halos get spherical only within the cores
- If inner parts have flattened density, outer parts have even greater weight.

Results from cosmological simulations - Substructure



Work in progress - Merging clusters

Dissosiative Clusters



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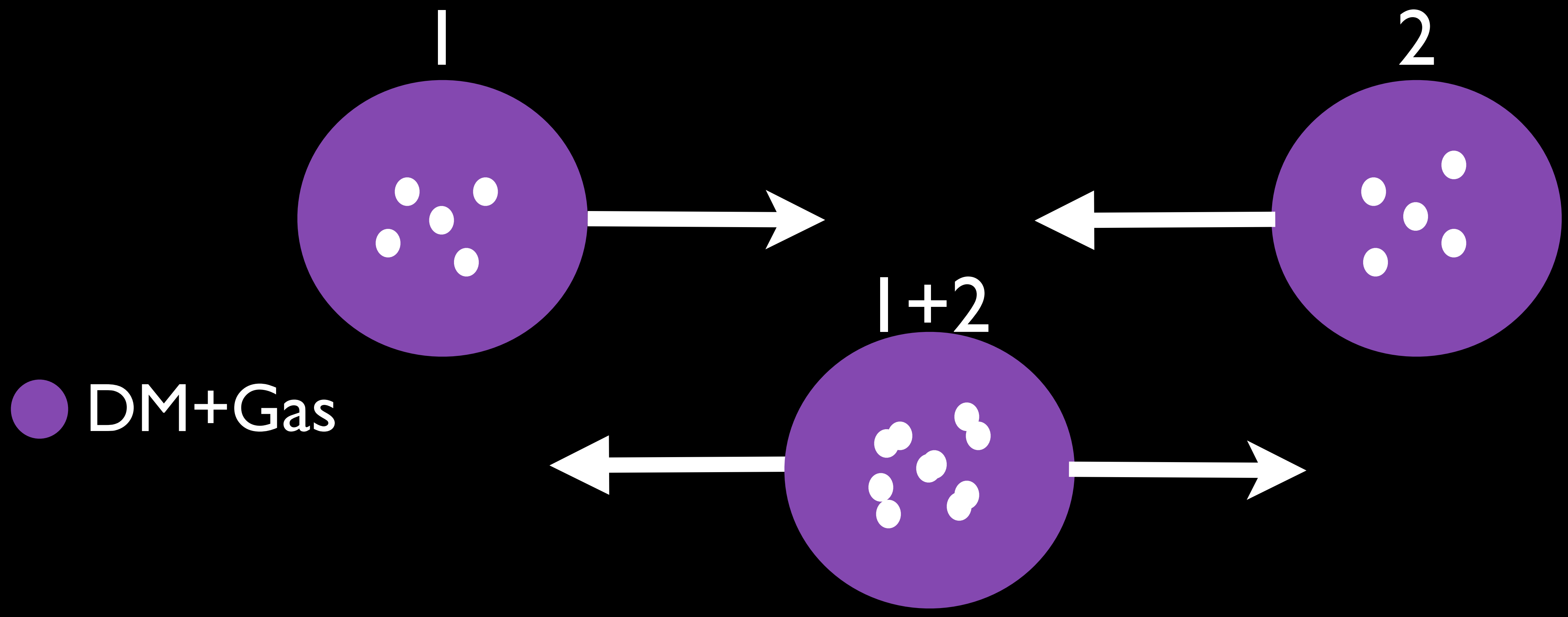

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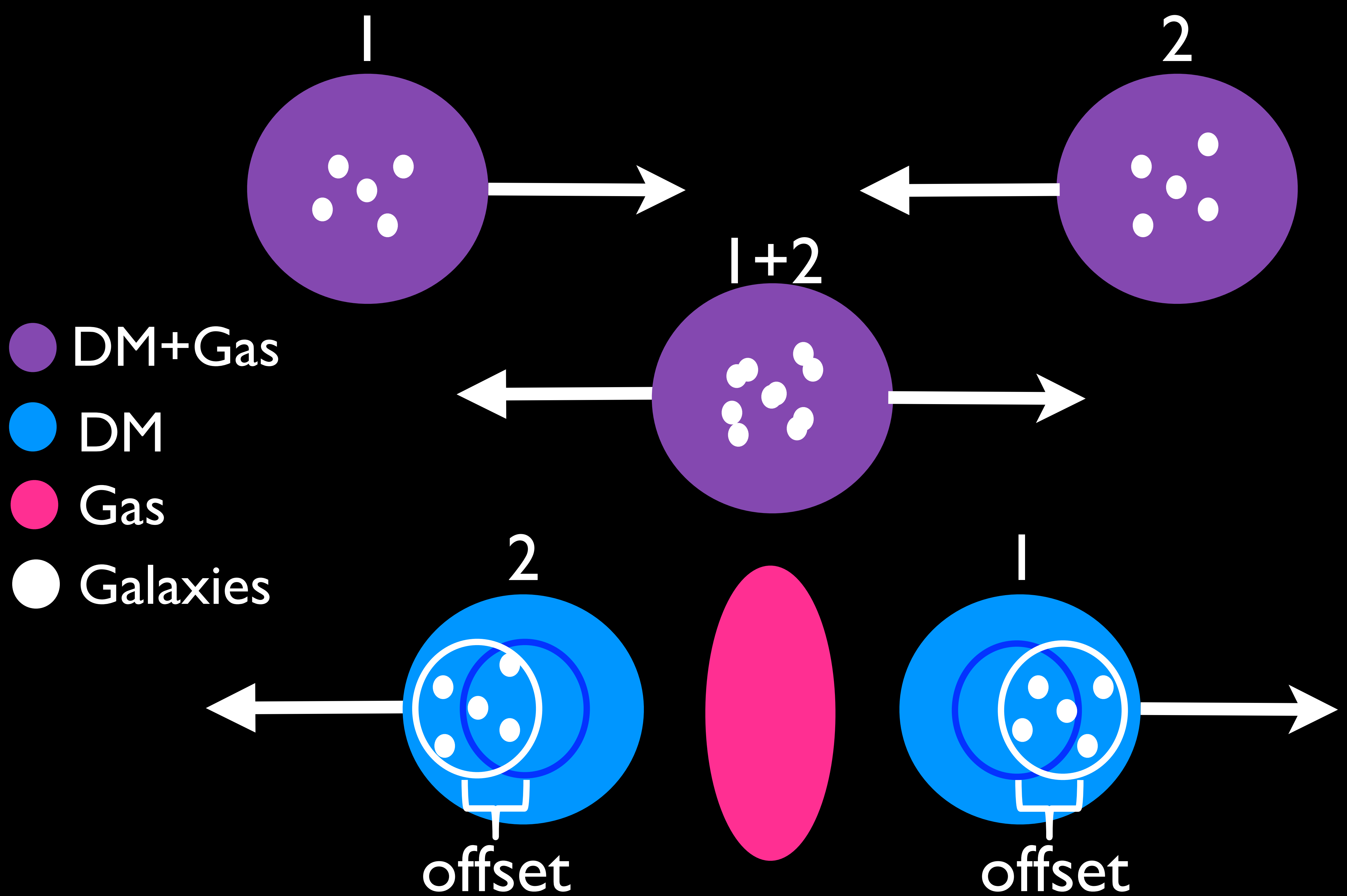
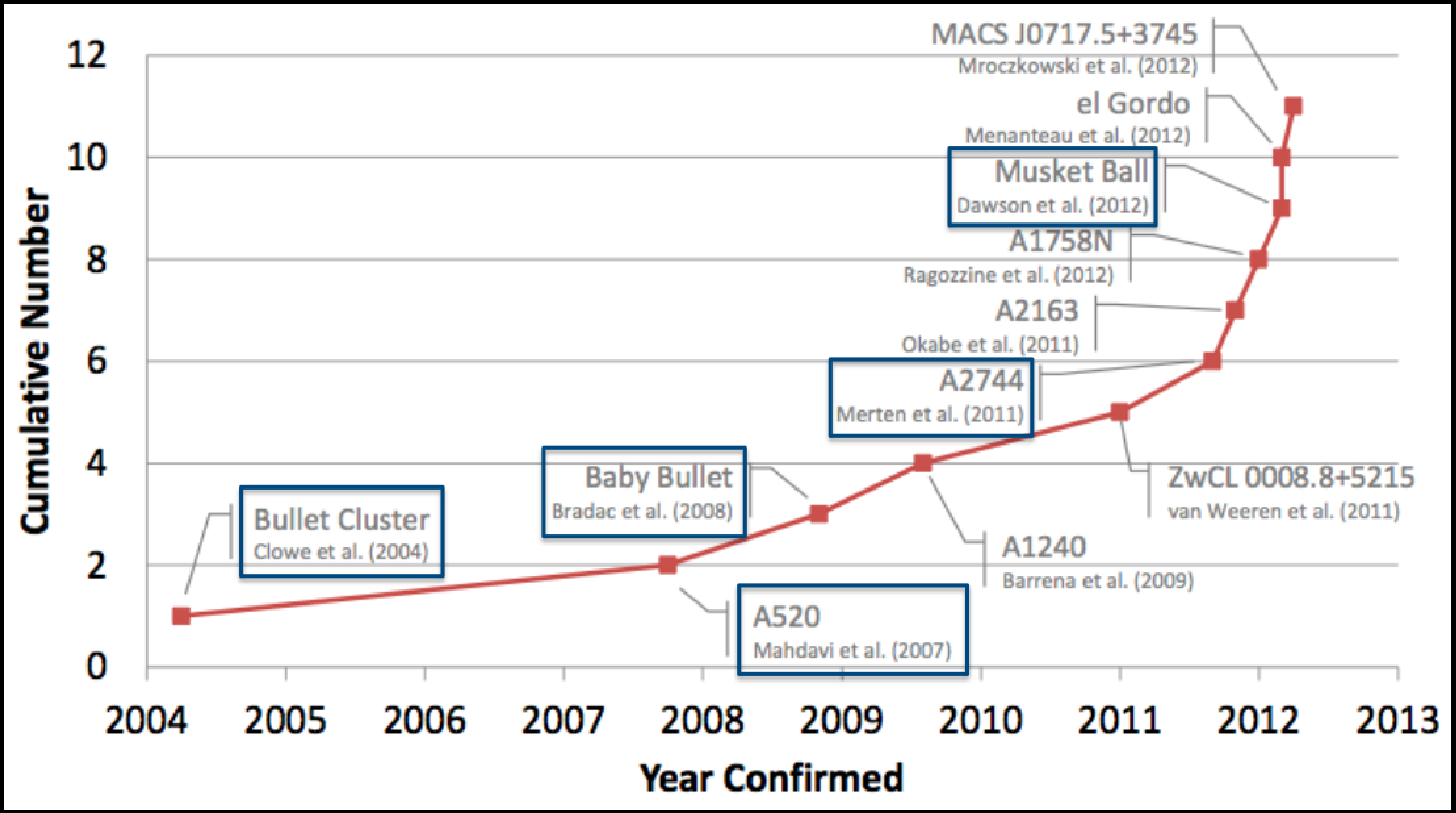


Work in progress - Merging clusters

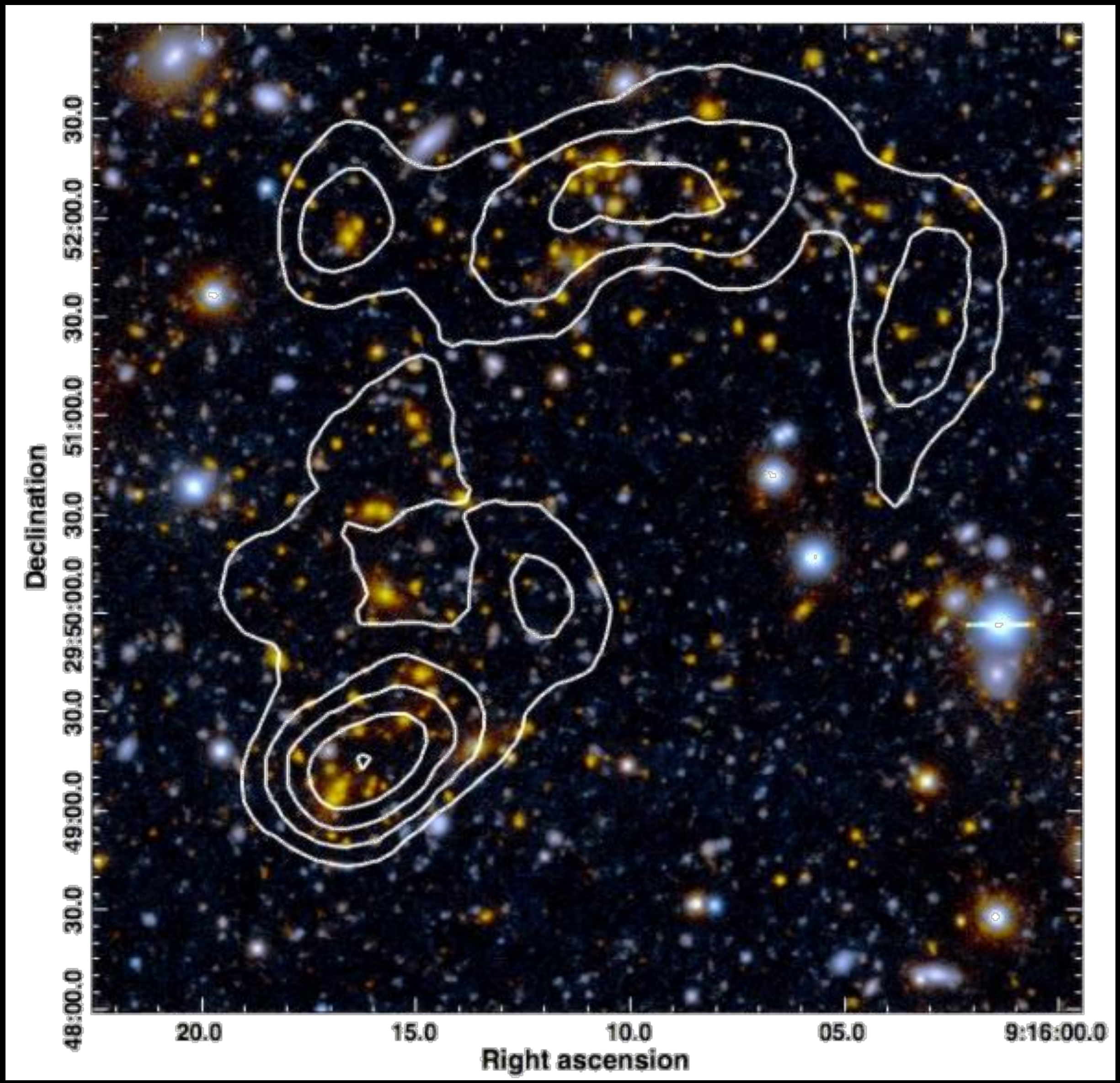
Observations



Work in progress - Merging clusters

Observations

The Musket Ball

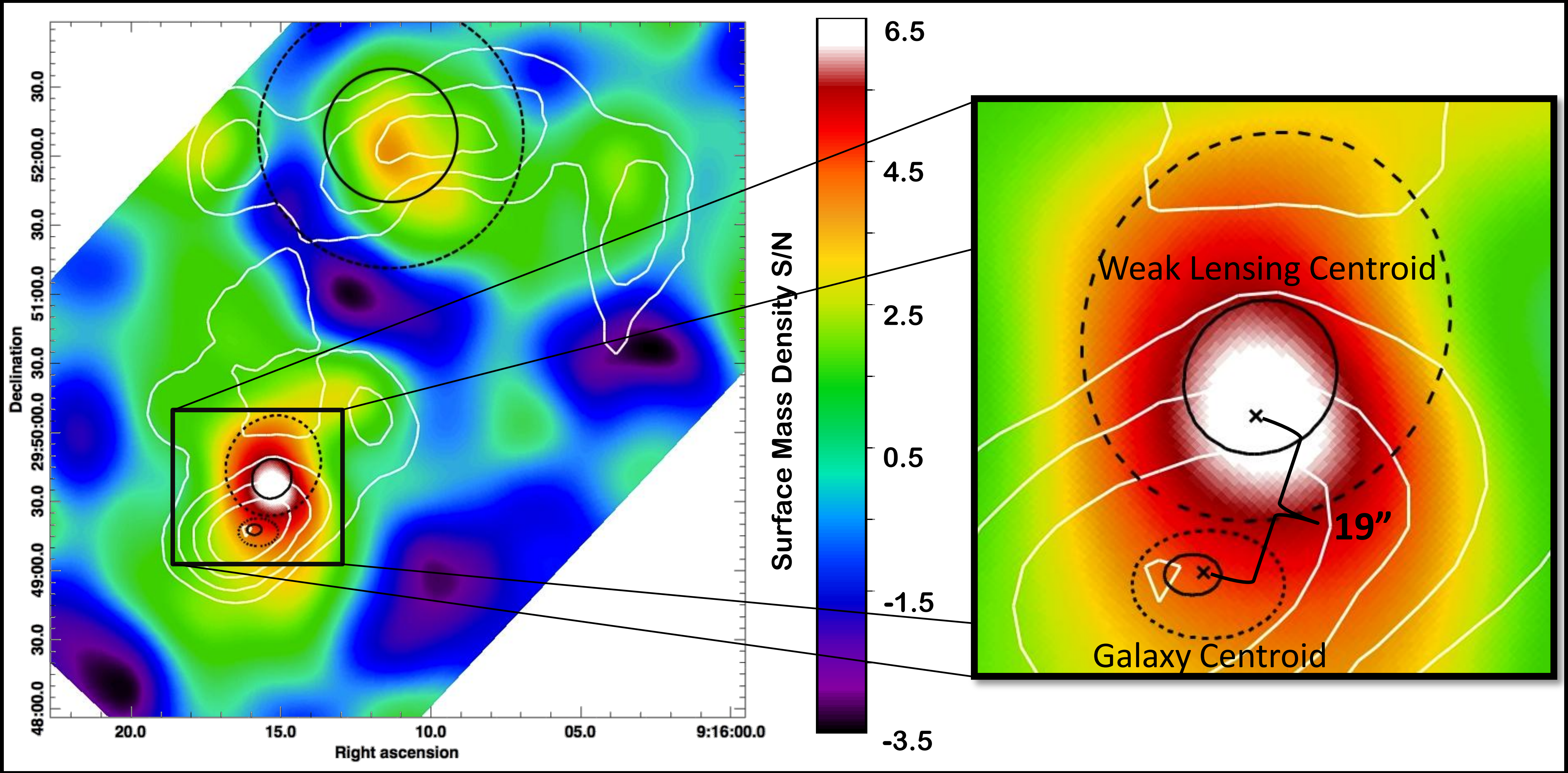


Dawson et al. 2012

Work in progress - Merging clusters

Observations

The Musket Ball



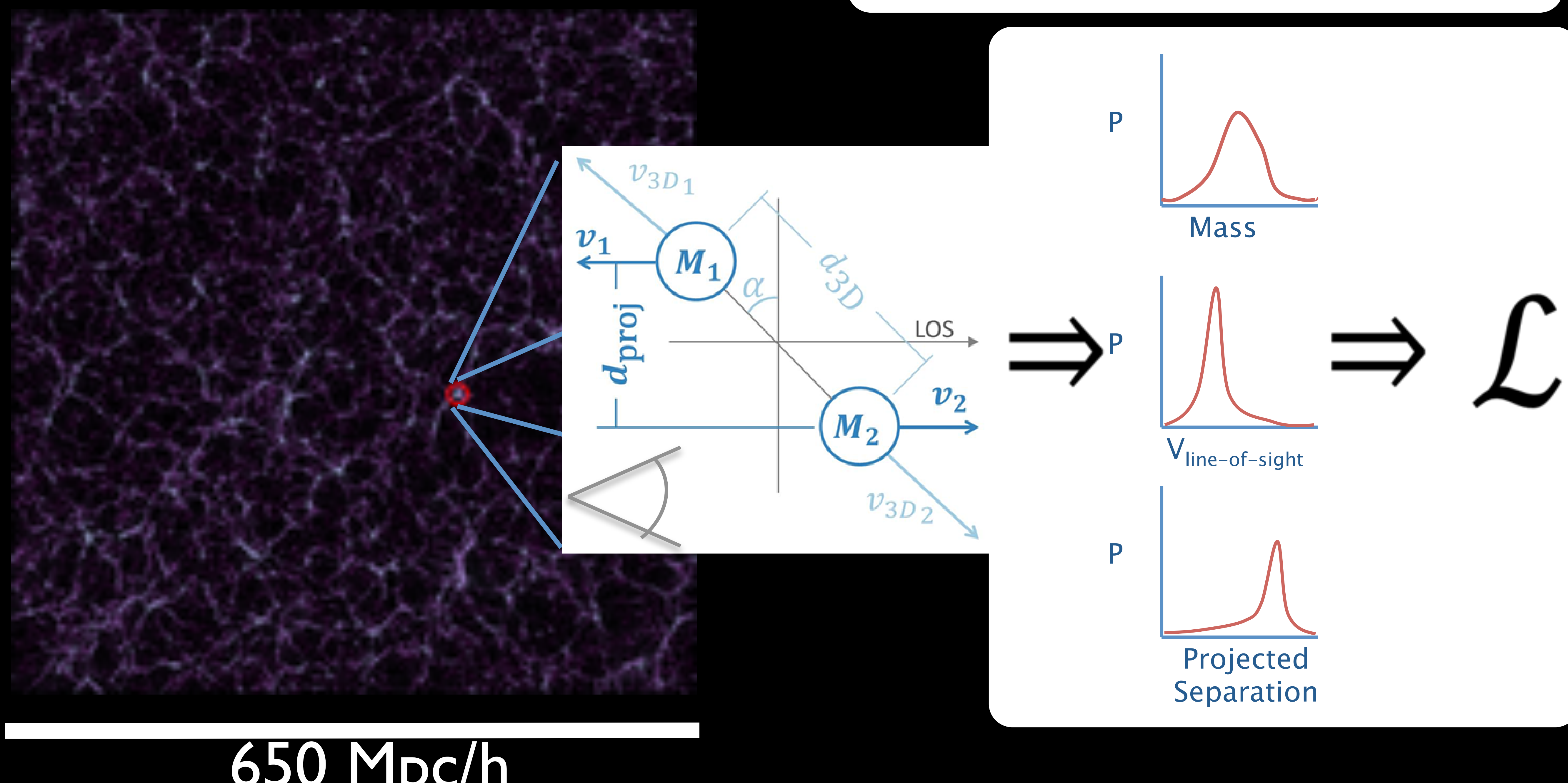
Dawson et al. 2012

Work in progress - Merging clusters

Predictions vs. Observations

Importance Sampling

MERGING CLUSTER COLLABORATION



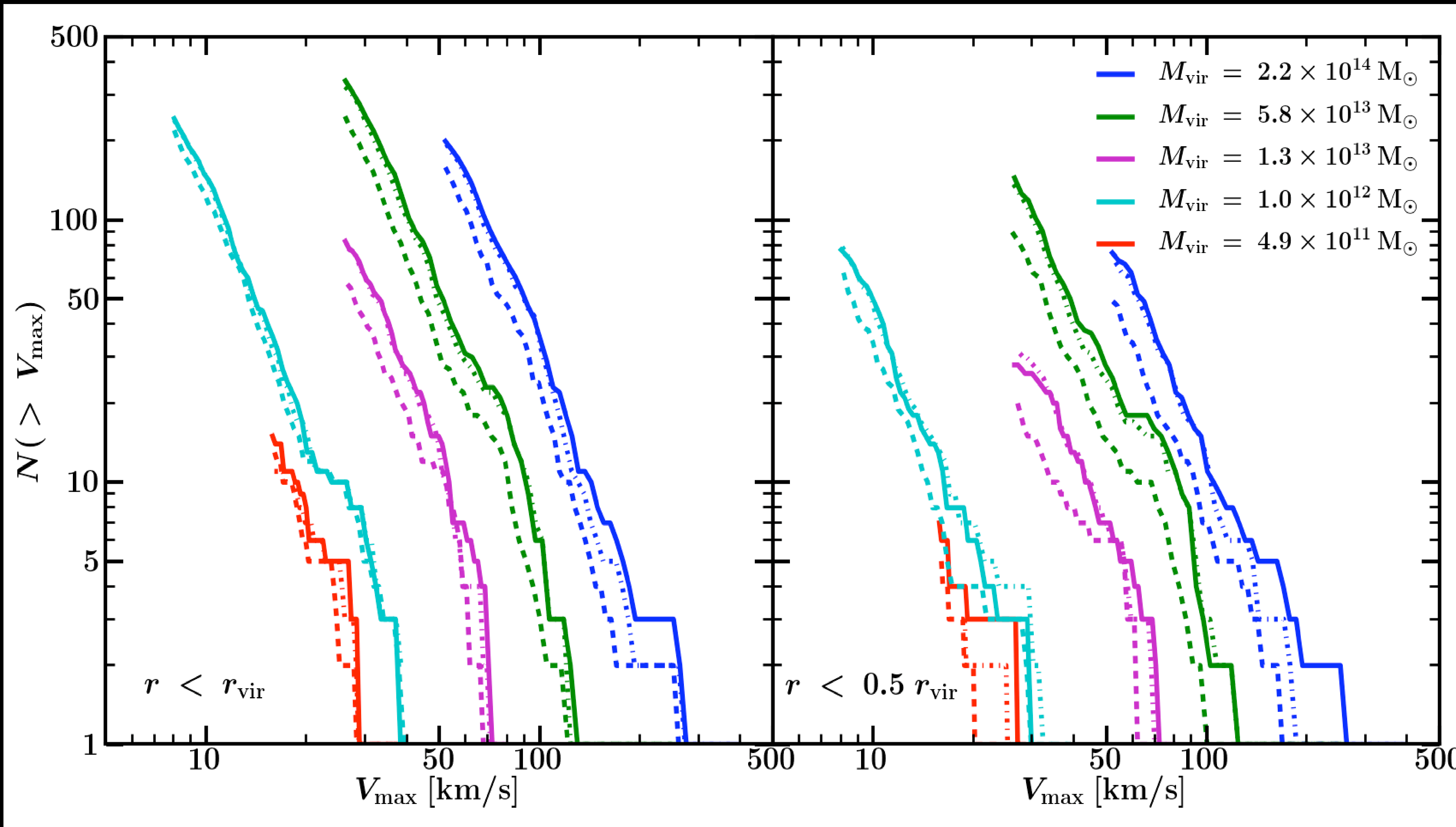
Conclusions

- SIDM with $\sigma/m < 1$ cm^2/g is not ruled out by any observations
- Cross-sections of $\sigma/m \sim 0.5$ cm^2/g can solve the cusp/core problem and TBTF while still consistent with cluster observations.
- We still need to understand the effect of Baryons however.
- Merging clusters are a promising way to probe the $\sigma/m > 0.1$ cm^2/g regime.

Thank You

Results from cosmological simulations - Substructure

SIDM & CDM have very similar subhalo Vmax functions



Rocha et al. 2013
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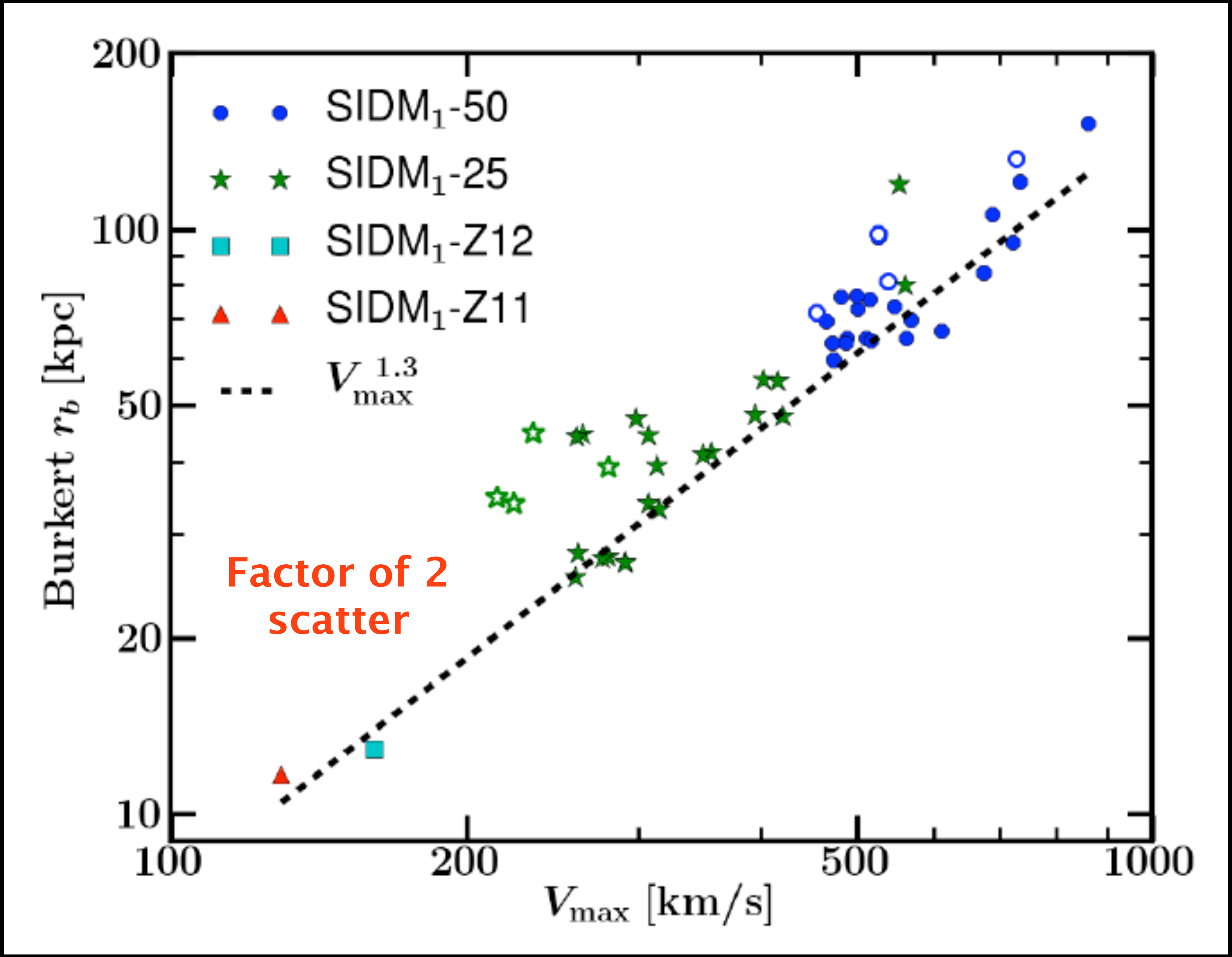
Results from cosmological simulations - Halo densities

Core Sizes



Dwarf galaxies

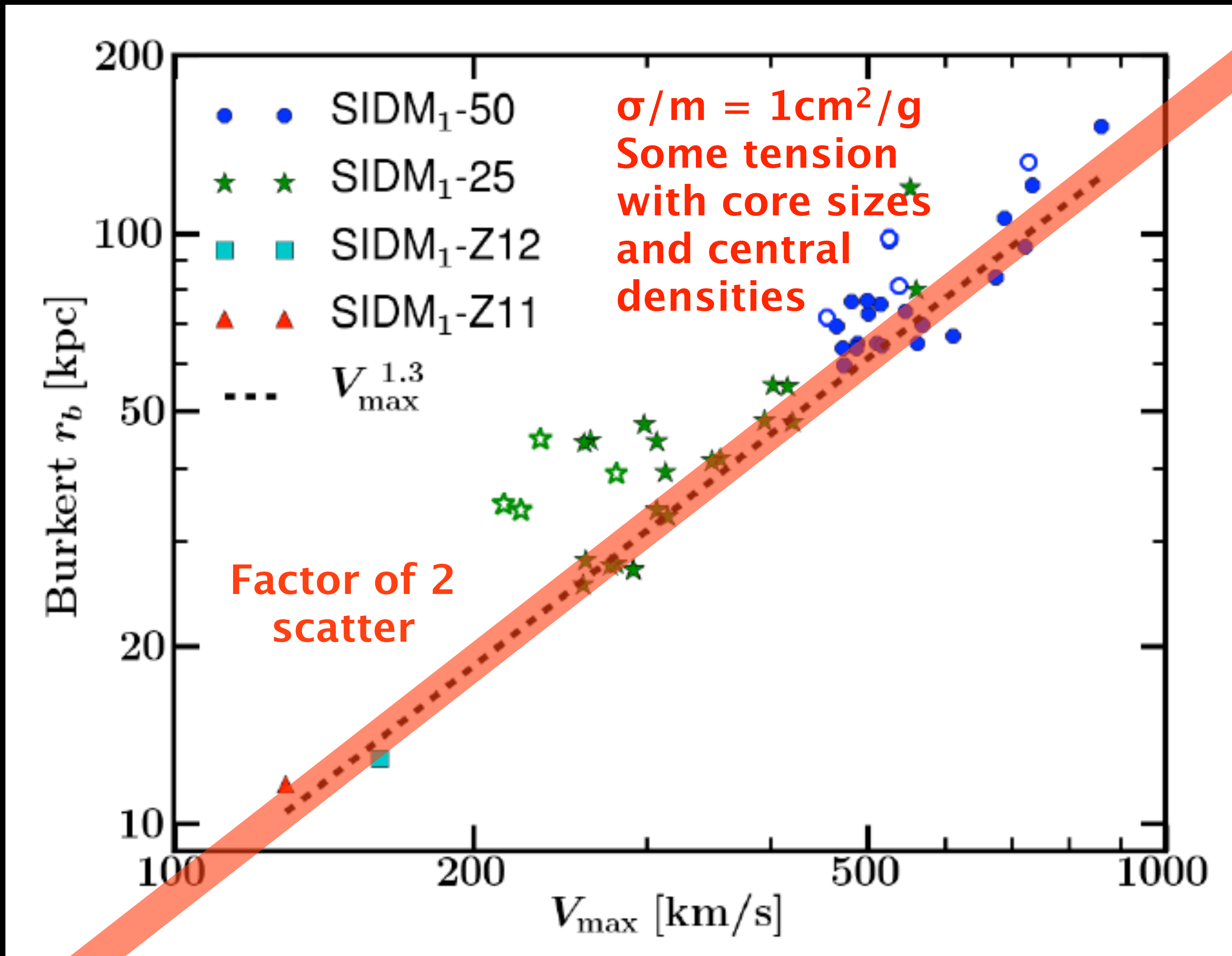
Milky Way

10^{15} $M_{\odot}$ clusters

Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo densities

Core Sizes



Dwarf galaxies

Milky Way

10^{15} $M_\odot$ clusters

Rocha et al. 2013
Peter et al. 2013

Tuesday, September 10, 13

Results from cosmological simulations - Halo densities

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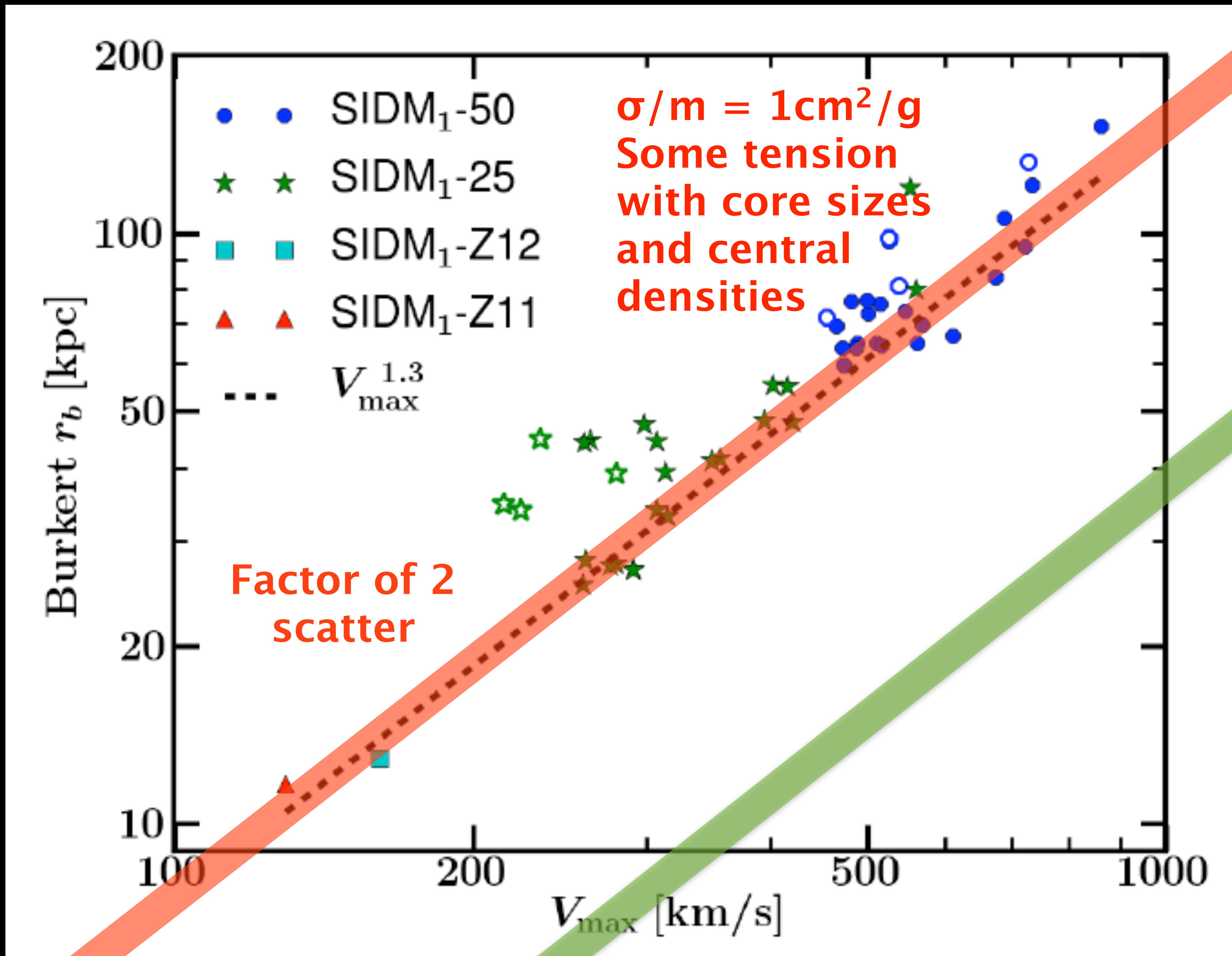

σ/m = 0.1 looks good across all scales!

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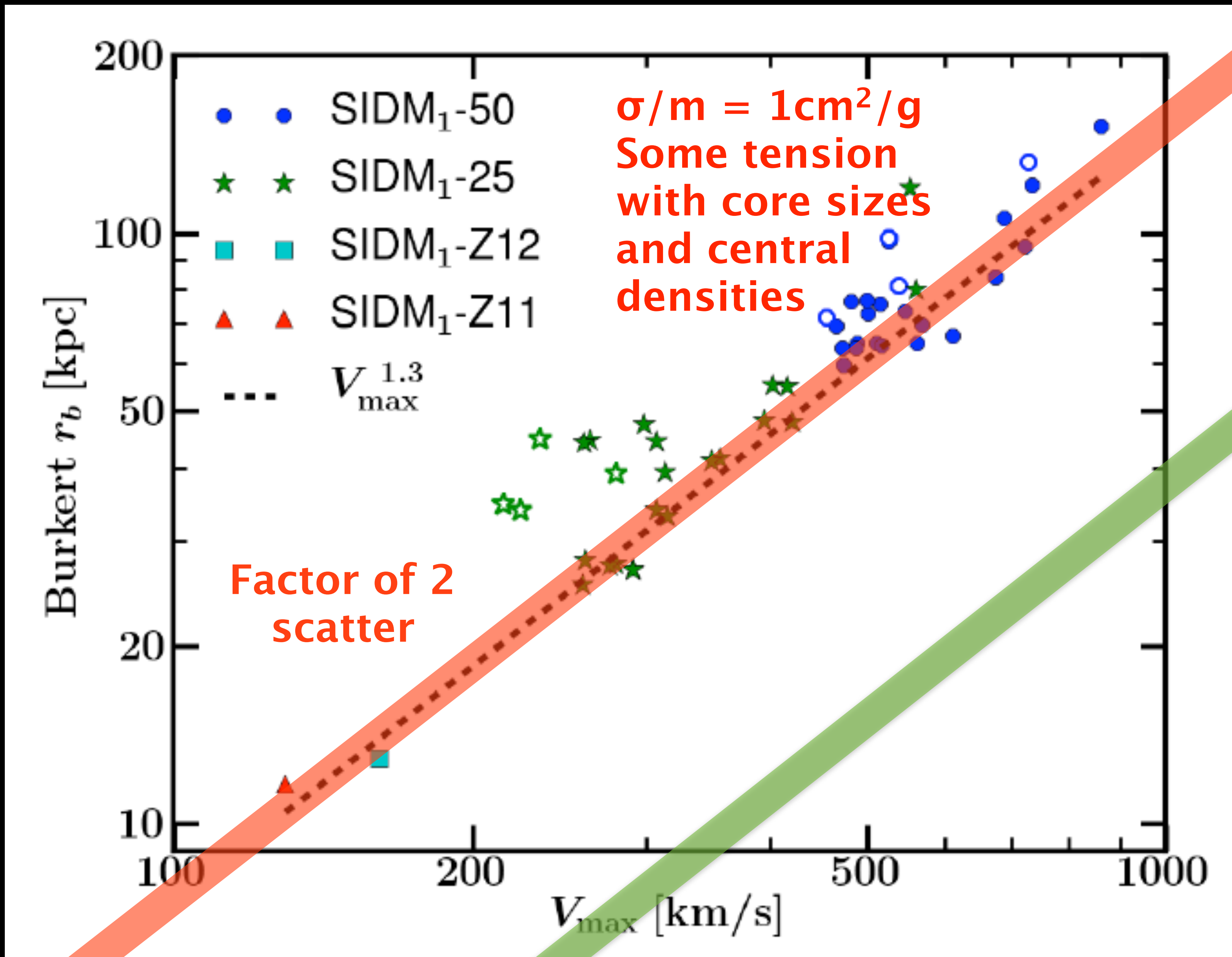
Work in progress - More simulations

Core Sizes



σ/m = 1cm²/g
Some tension with core sizes and central densities

Factor of 2 scatter

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Dwarf galaxies

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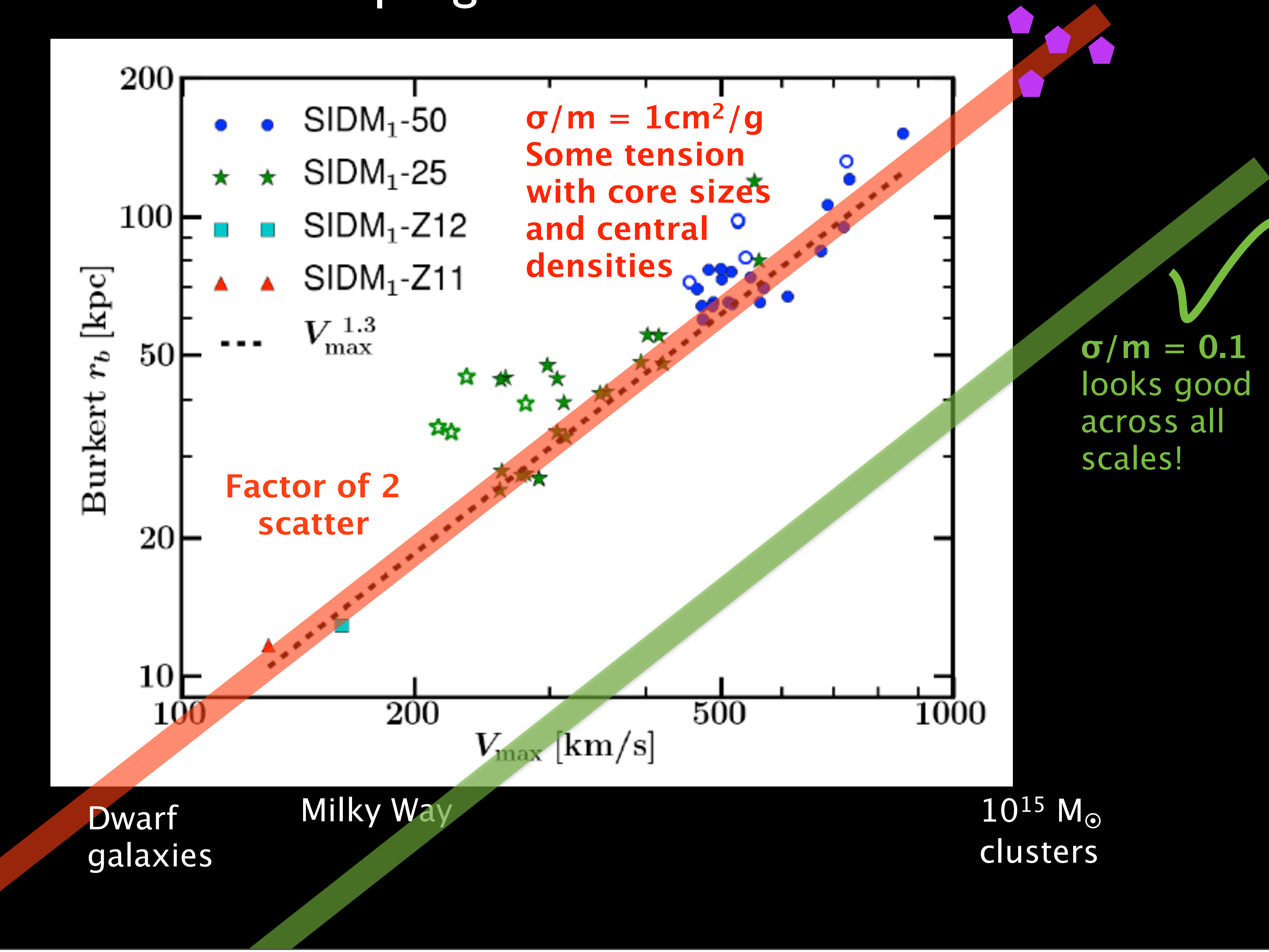

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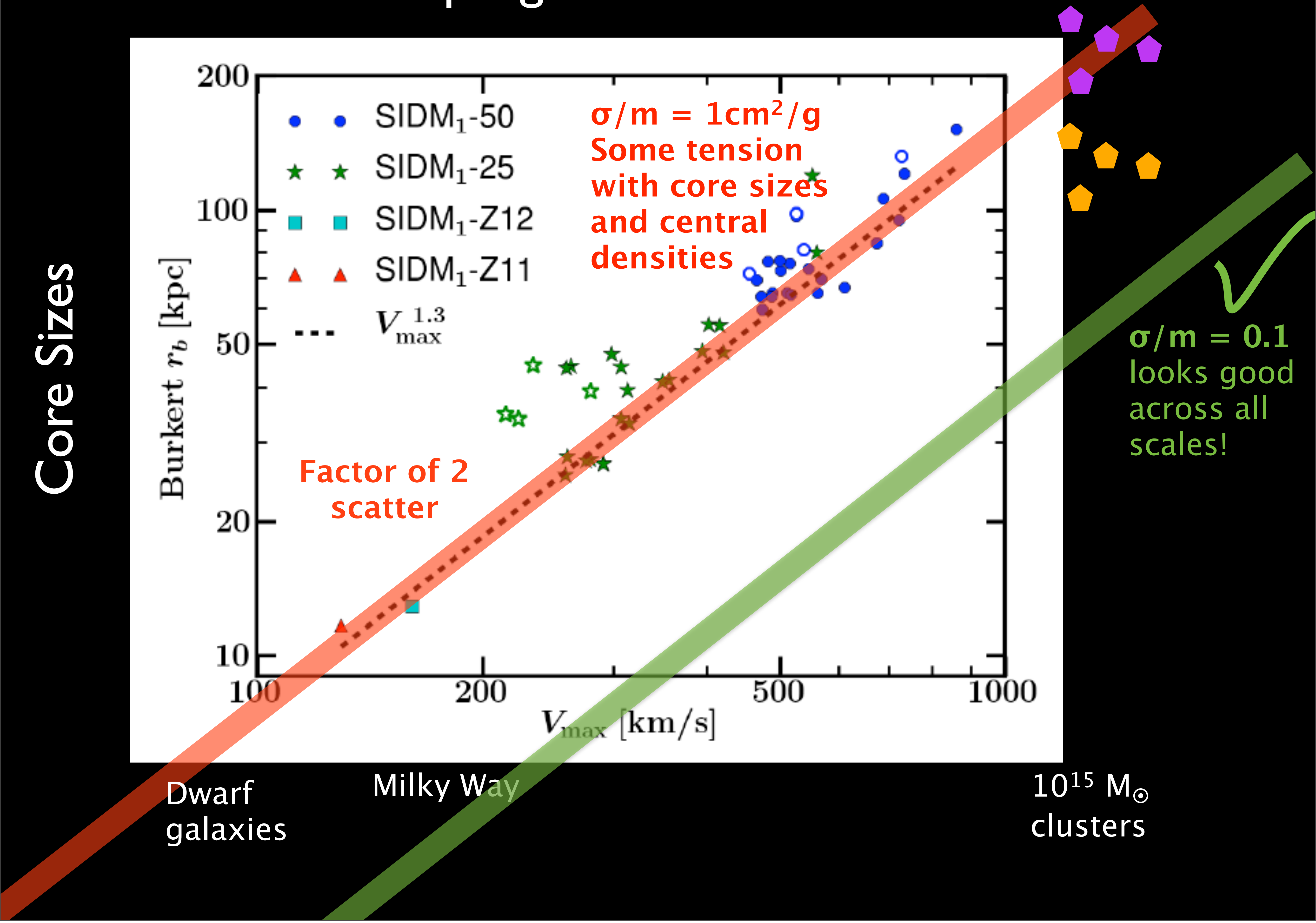

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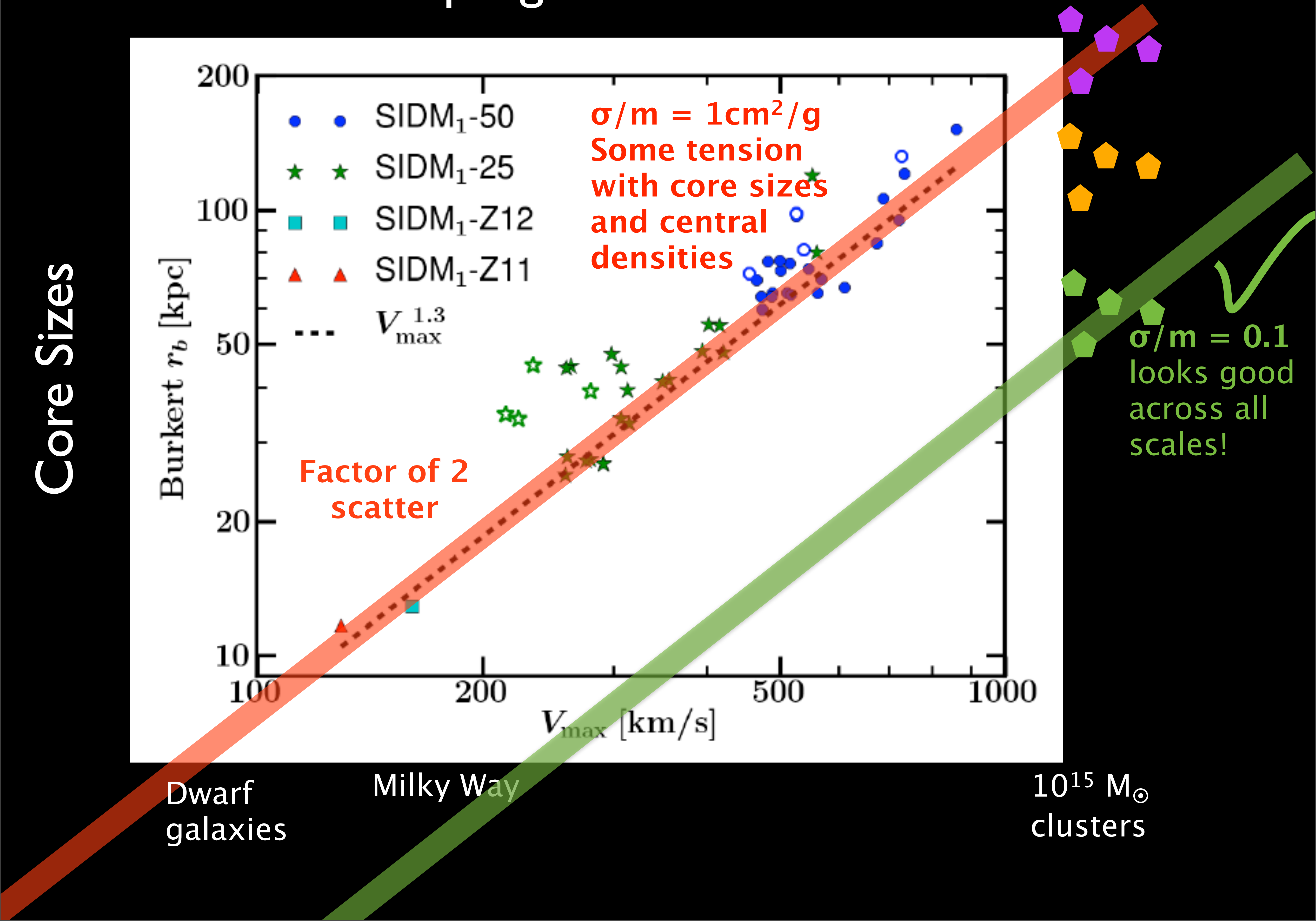
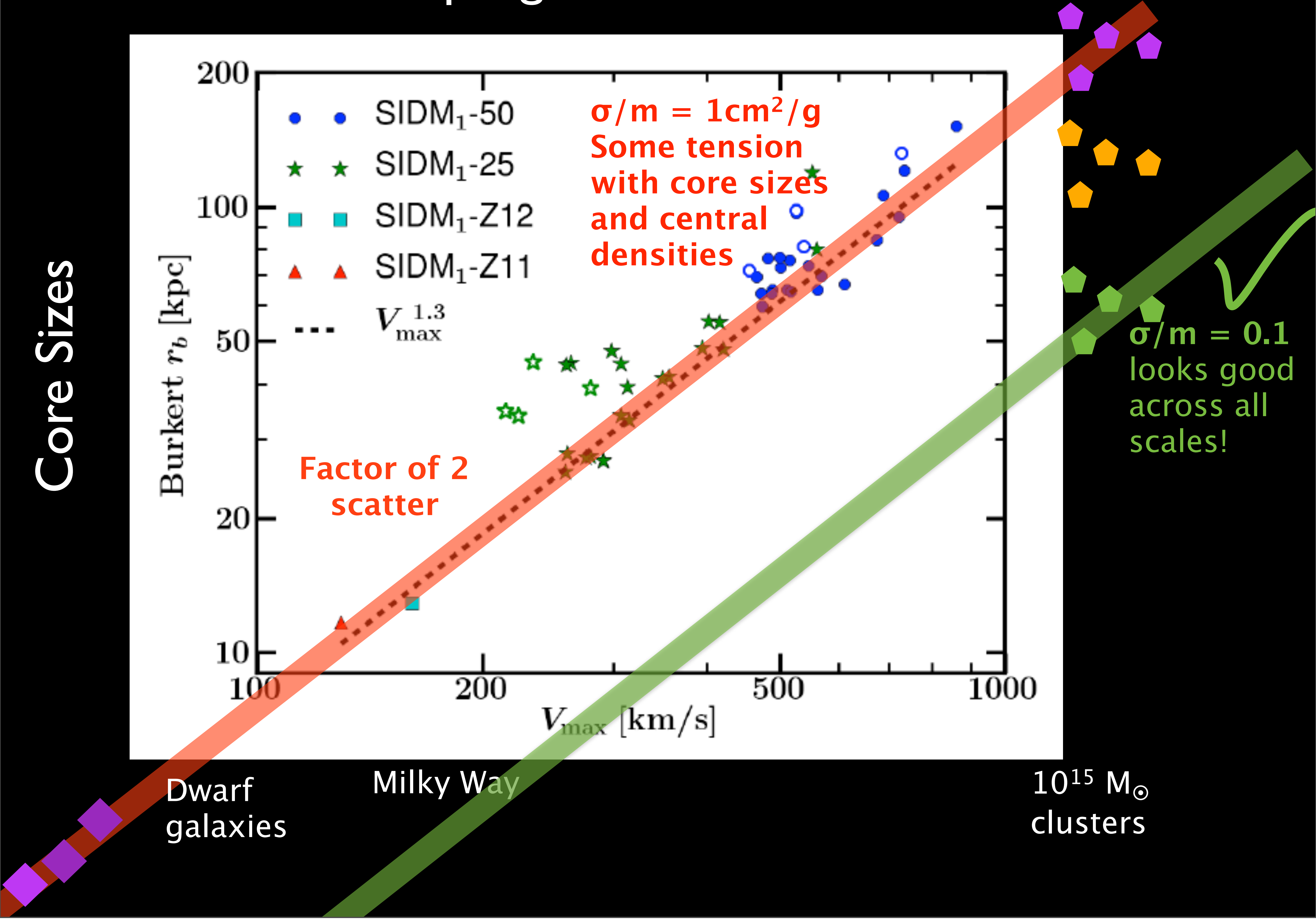
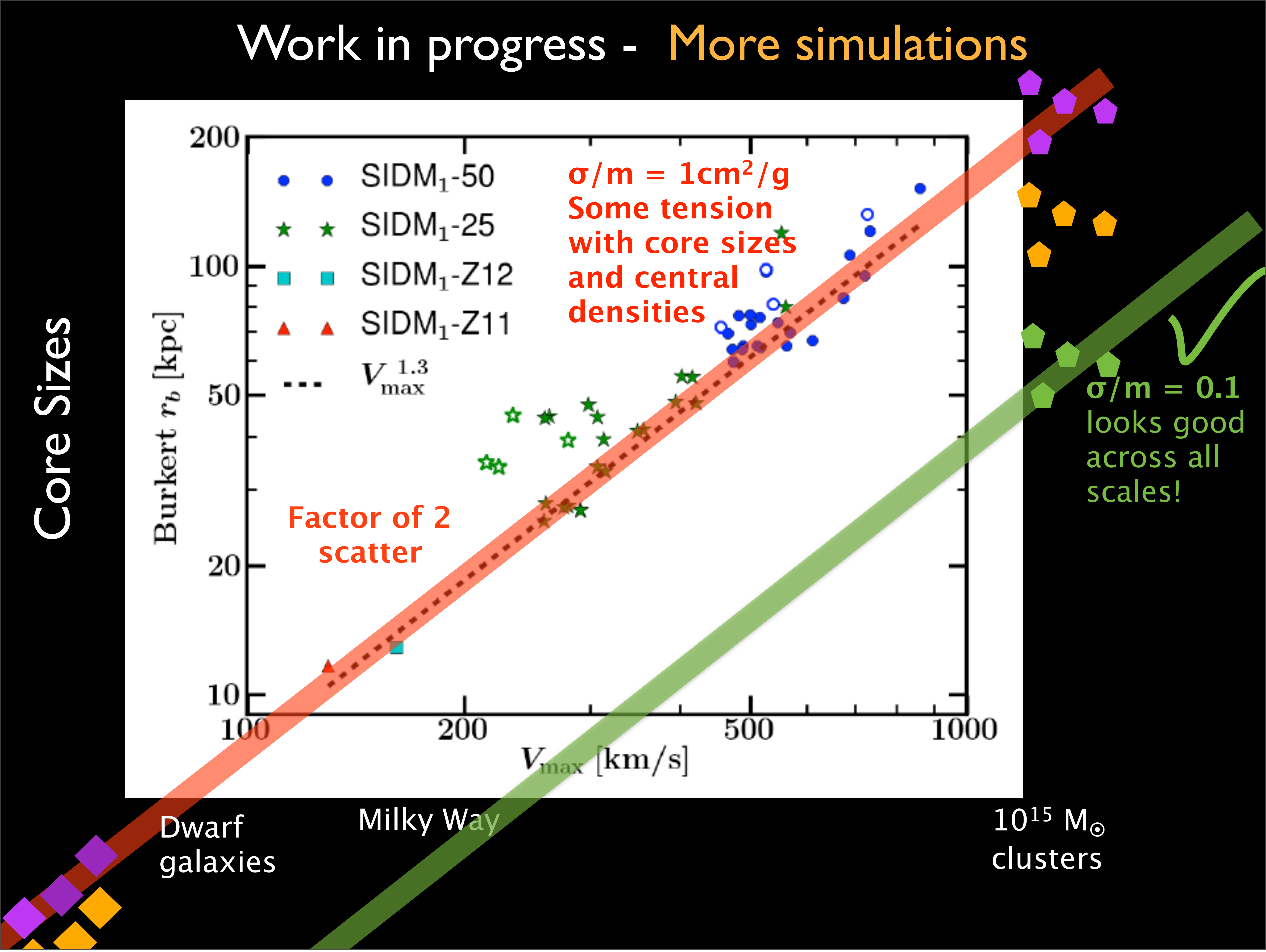


Work in progress - More simulations




Work in progress - More simulations
Core Sizes
Burkert r_b [kpc]
200
100
50
20
10
SIDM$_1$-50
SIDM$_1$-25
SIDM$_1$-Z12
SIDM$_1$-Z11
$V_{\rm max}^{1.3}$
σ/m = 1cm²/g
Some tension with core sizes and central densities
Factor of 2 scatter
100
200
500
1000
$V_{\rm max}$ [km/s]
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Milky Way
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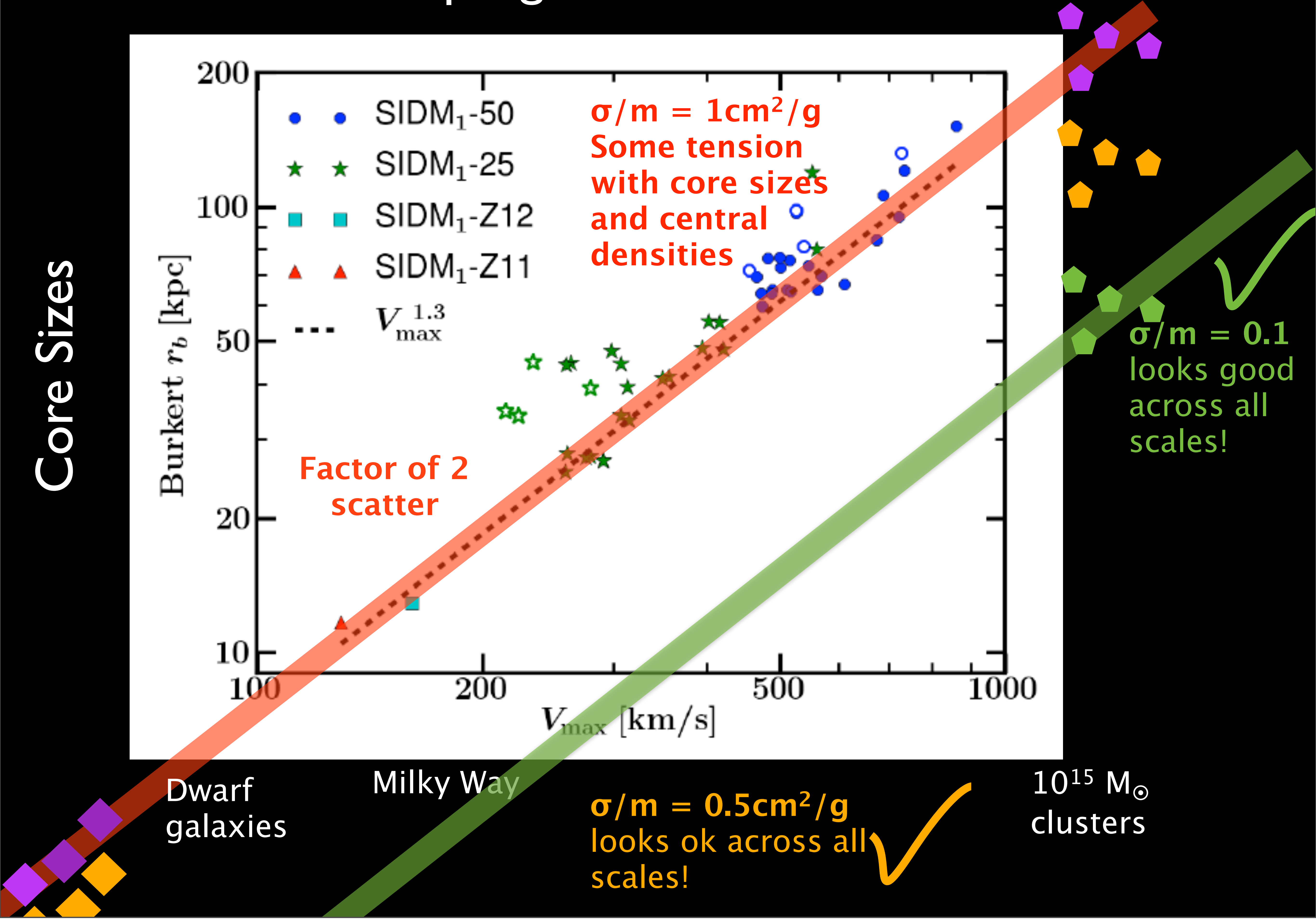
Work in progress - More simulations



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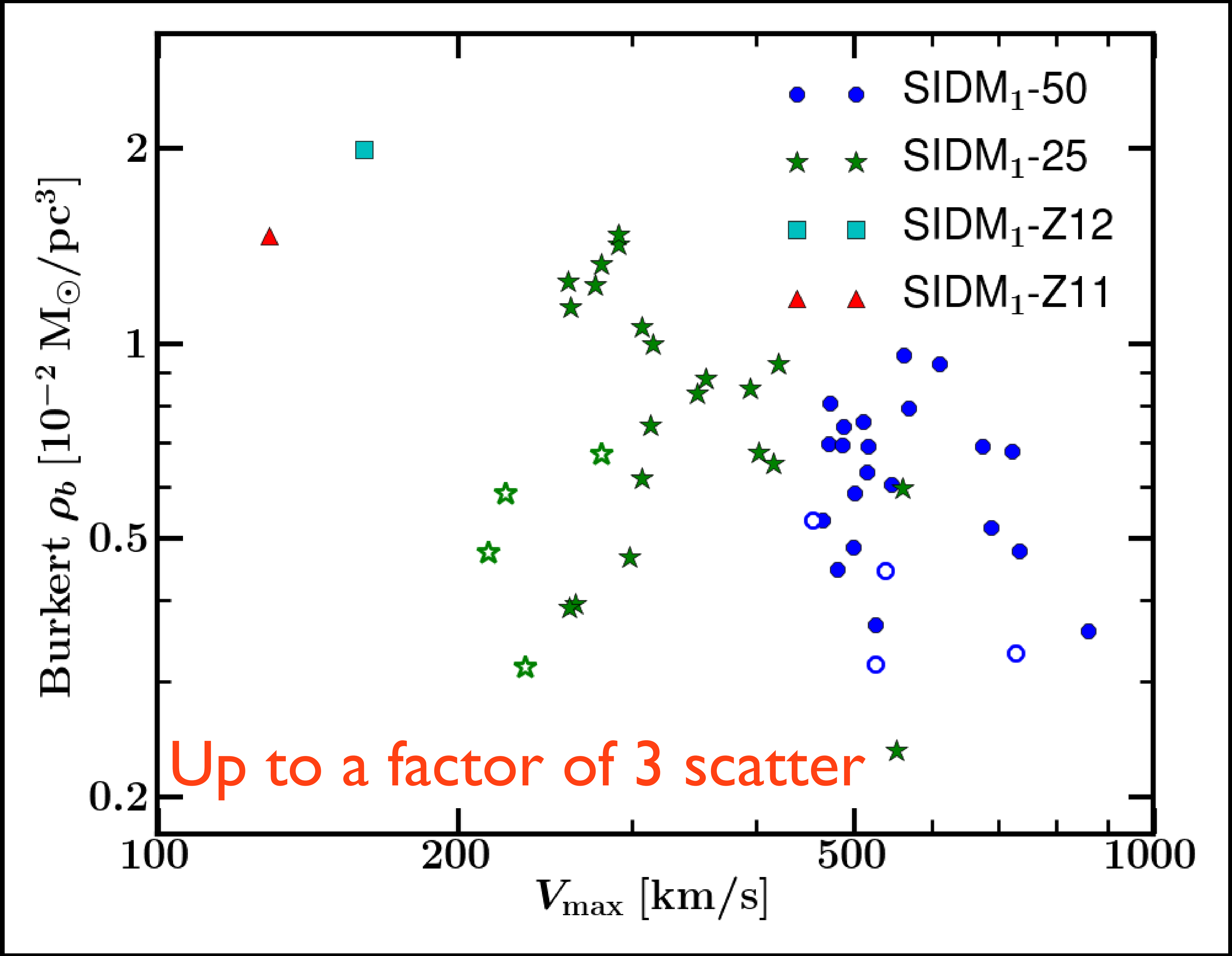


Rocha et al. 2013
Peter et al. 2013

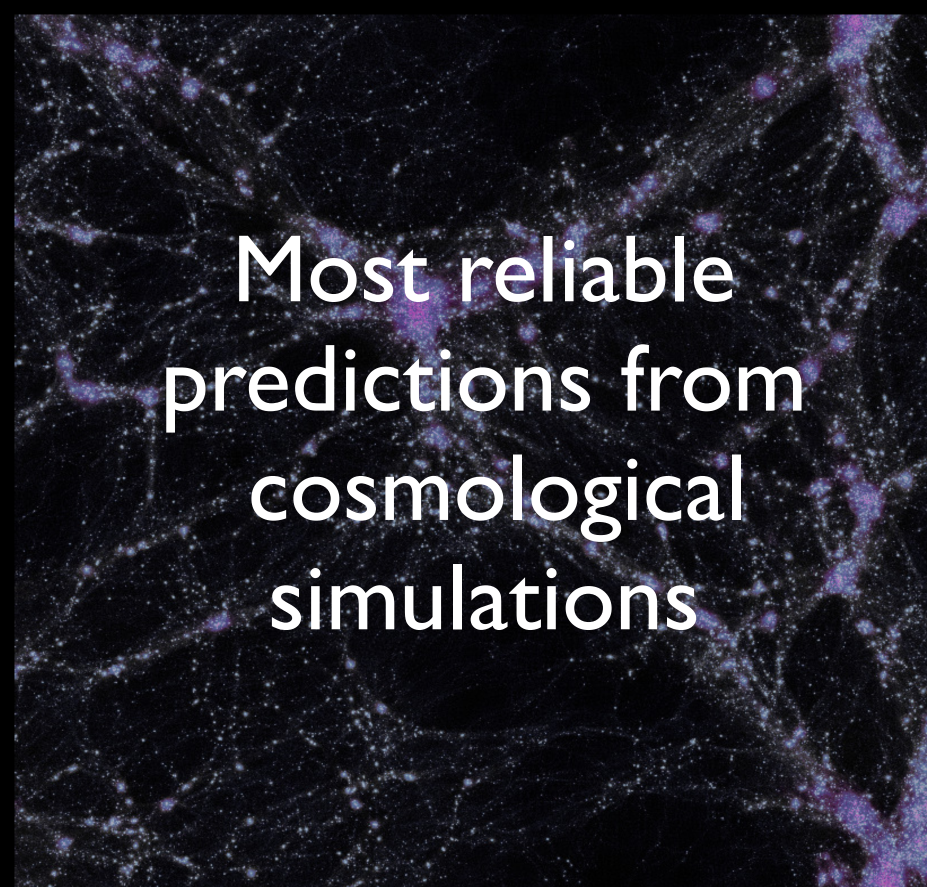
$\sigma/m = 1\ \mathrm{cm}^2\ /\mathrm{g}$

Astrophysical Constraints

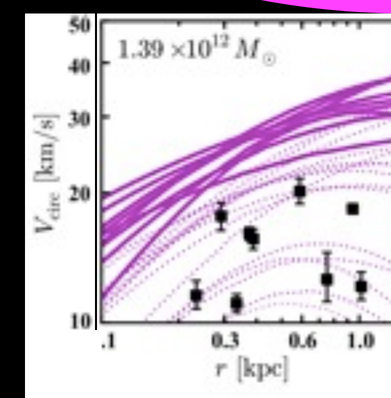
Phenomenology → Predictions ⇄ Observations

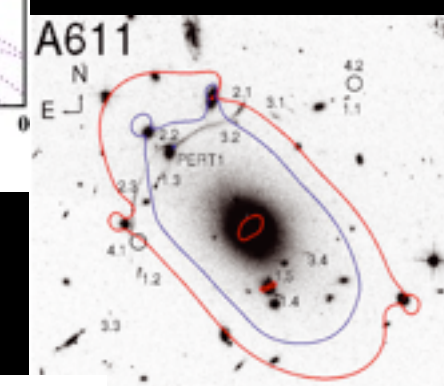
σ/m

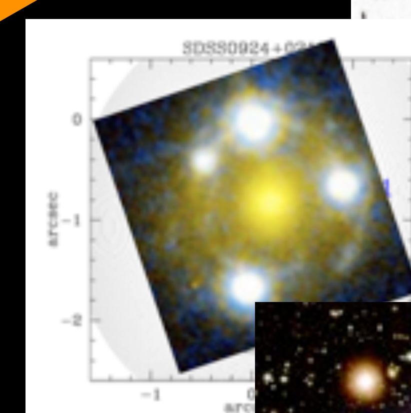
- Core sizes & densities
- Shapes
- Substructure
- Merging clusters: offsets & M/L ratios

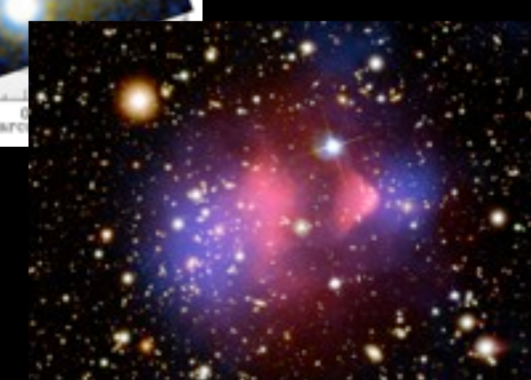


σ/m ⟷









Is this a crazy idea?

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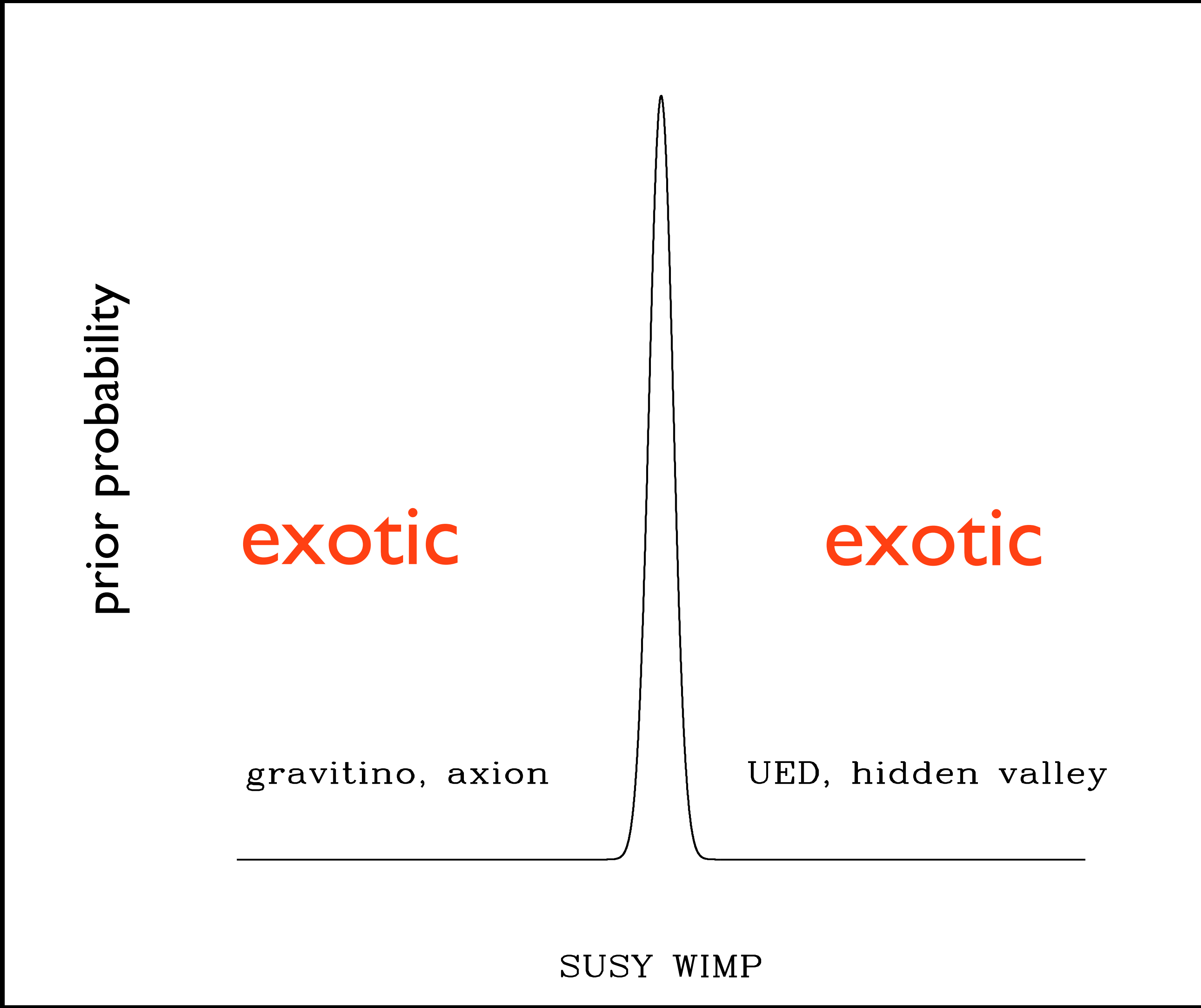
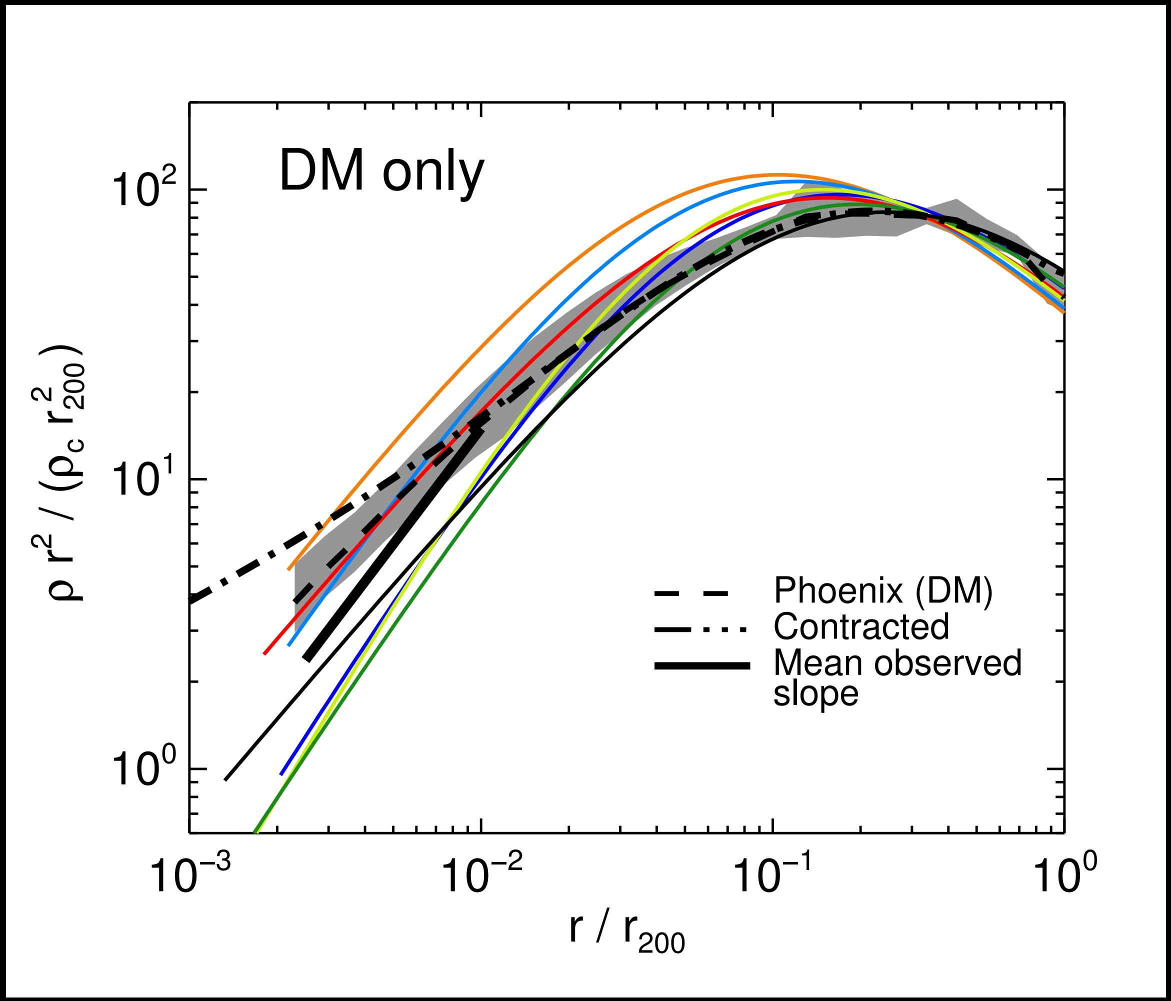
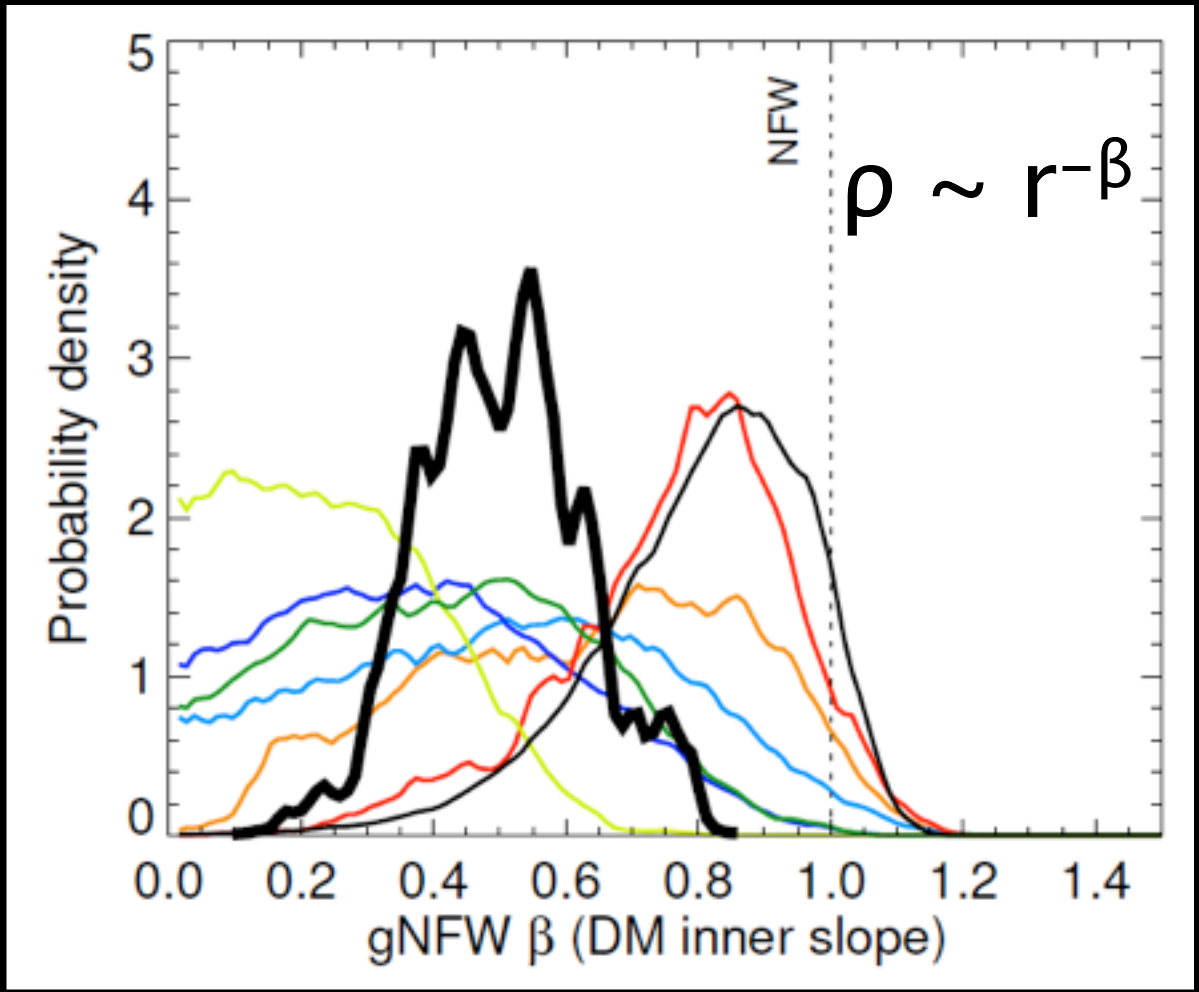


Image courtesy of Annika Petter

Evidence for lower central DM densities than DM only simulations predict across all scales

Galaxy cluster densities



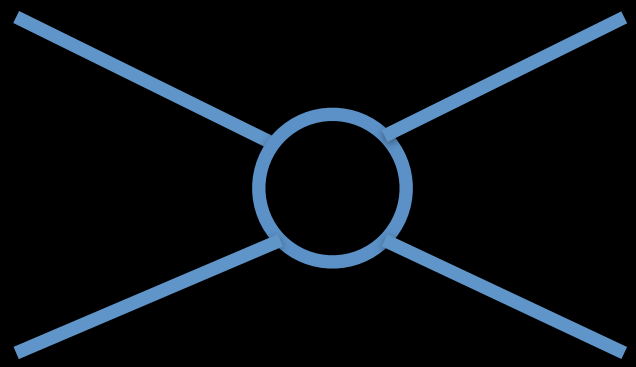


Galaxy Clusters
(~ 10^{14}–10^{15} $M_\odot$ halos)

Allow cores of ~30 kpc

(Newman+ 2012a,b)

Simulating DM Self-Interactions - A new self-consistent algorithm



Spergerl & Steinhardt 2000 $\longrightarrow$

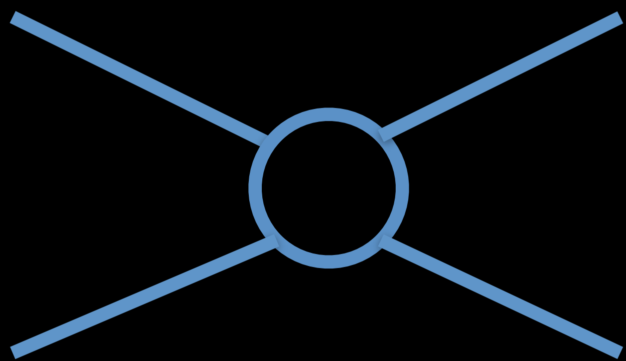
Elastic - Velocity Independent - Isotropic

$$\Gamma = \rho \left(\frac{\sigma}{m} \right) v_{rel}$$

phase-space evolution given by the Boltzmann Eq. with a hard-sphere collision operator

$$\frac{Df(\mathbf{x}, \mathbf{v}, t)}{Dt} = \Gamma[f, \sigma]$$
$$= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} \left|\mathbf{v} - \mathbf{v}_1\right| \left[f(\mathbf{x}, \mathbf{v}', t) f(\mathbf{x}, \mathbf{v}_1', t) - f(\mathbf{x}, \mathbf{v}, t) f(\mathbf{x}, \mathbf{v}_1, t)\right]$$

Simulating DM Self-Interactions - A new self-consistent algorithm



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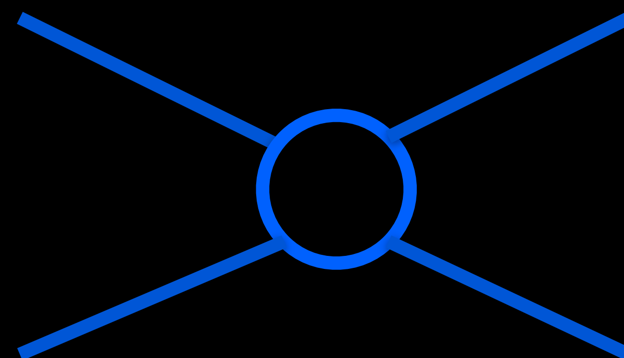
$$\hat{f}(\mathbf{x}, \mathbf{v}, t) = \sum_i (M_i/m) W(|\mathbf{x} - \mathbf{x}_i|; h_i) \delta^3(\mathbf{v} - \mathbf{v}_i)$$

Simulating DM Self-Interactions



large mean free paths

Collisionality

short mean free paths

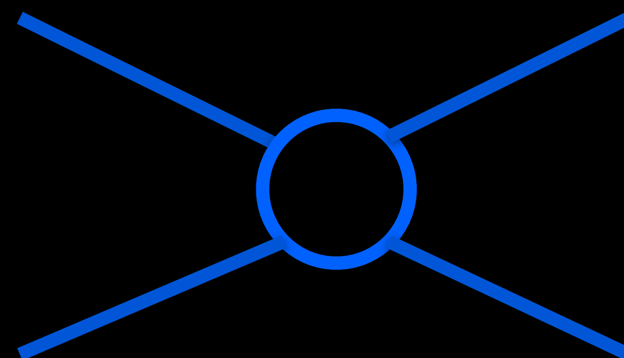
Spergerl & Steinhardt 2000

$$\frac{\sigma}{m} = 0.1 - 100\ \mathrm{cm}^2/\mathrm{g}$$

Vlavsov equation solved with collisionless N-body

Fluid equations solved with hydro methods

Simulating DM Self-Interactions



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Vlavsov equation solved with collisionless N-body

Fluid equations solved with hydro methods

Need to step back and derive an algorithm from the Boltzmann Equation

Simulating DM Self-Interactions - A new self-consistent algorithm

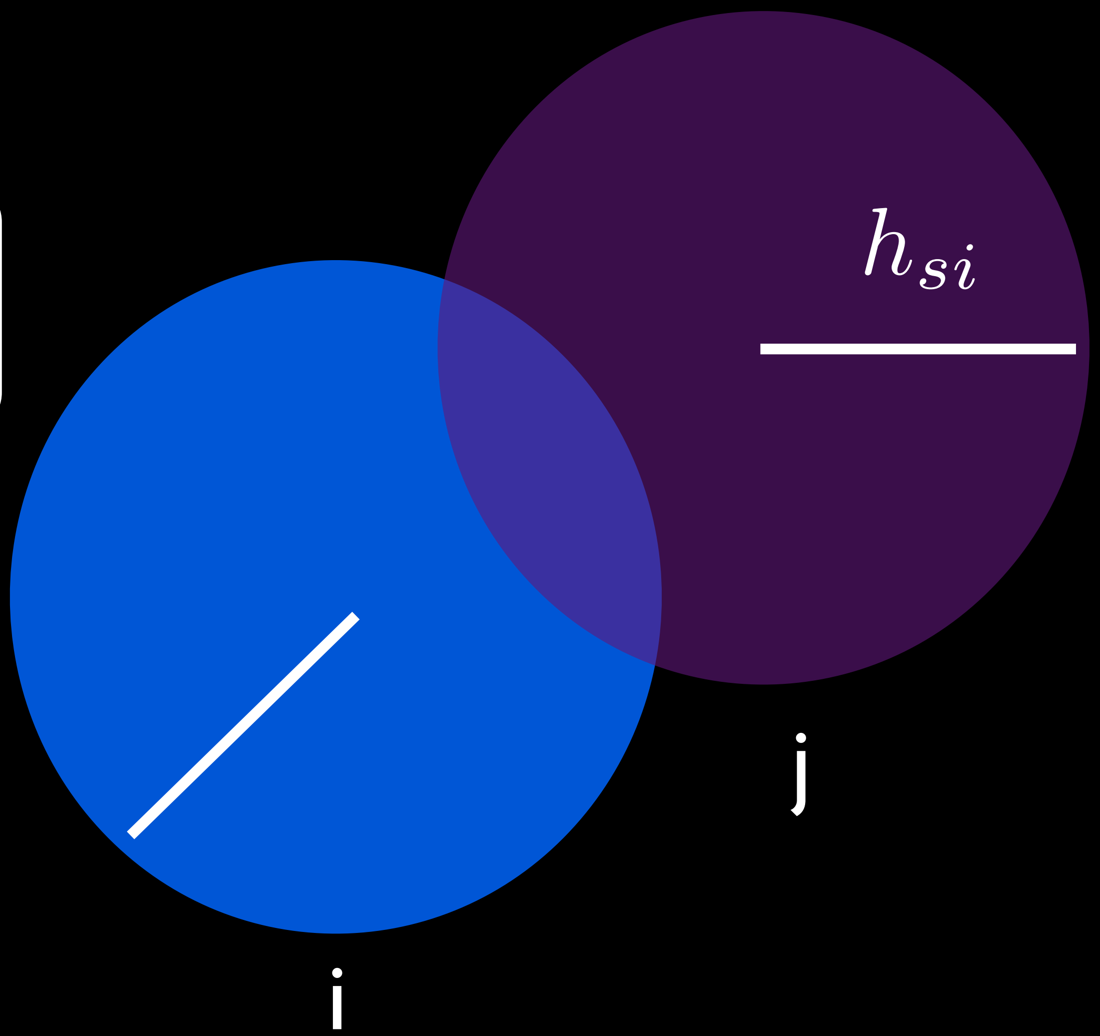
Consistent Pair-Wise Probability

$$\Gamma(i|j) = (\sigma/m) m_{\rm p} |\mathbf{v}_i - \mathbf{v}_j| g_{ji}$$

$$g_{ji} = \int_0^{h_{\rm si}} d^3\mathbf{x}' W(|\mathbf{x}'|, h_{\rm si}) W(|\delta\mathbf{x}_{ji} + \mathbf{x}'|, h_{\rm si})$$

$$P(i|j) = \Gamma(i|j)\,\delta t$$

$$P(i|j) = P(j|i)$$



Simulating DM Self-Interactions - A new self-consistent algorithm

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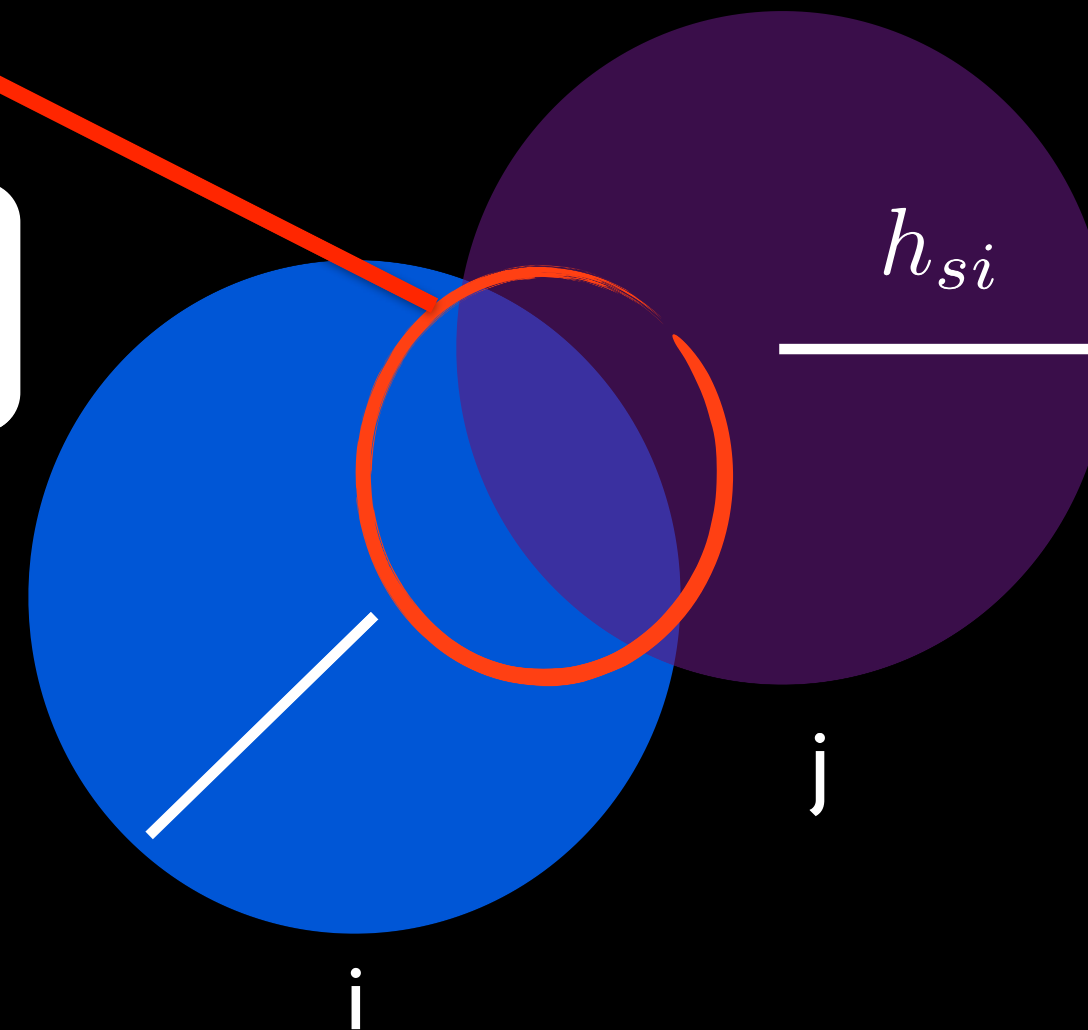
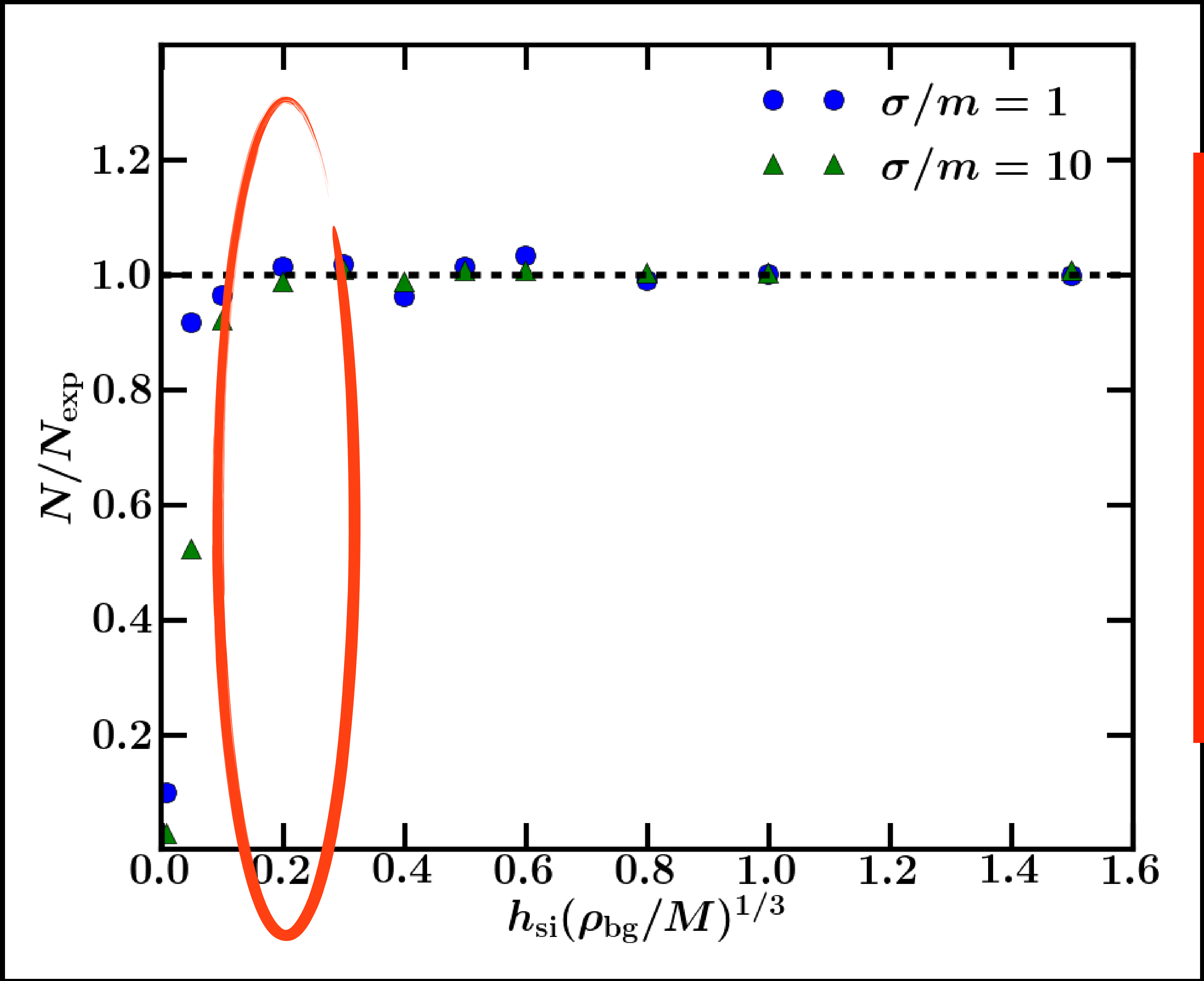
$$P(i|j) = P(j|i)$$



Simulating DM Self-Interactions - A new self-consistent algorithm

Wind Tunnel Test



Interaction rate converges to the expected value when h_{si} >0.2* (the interparticle separation)

Rocha et al. 2013
Peter et al. 2013

Simulating DM Self-Interactions - A new self-consistent algorithm

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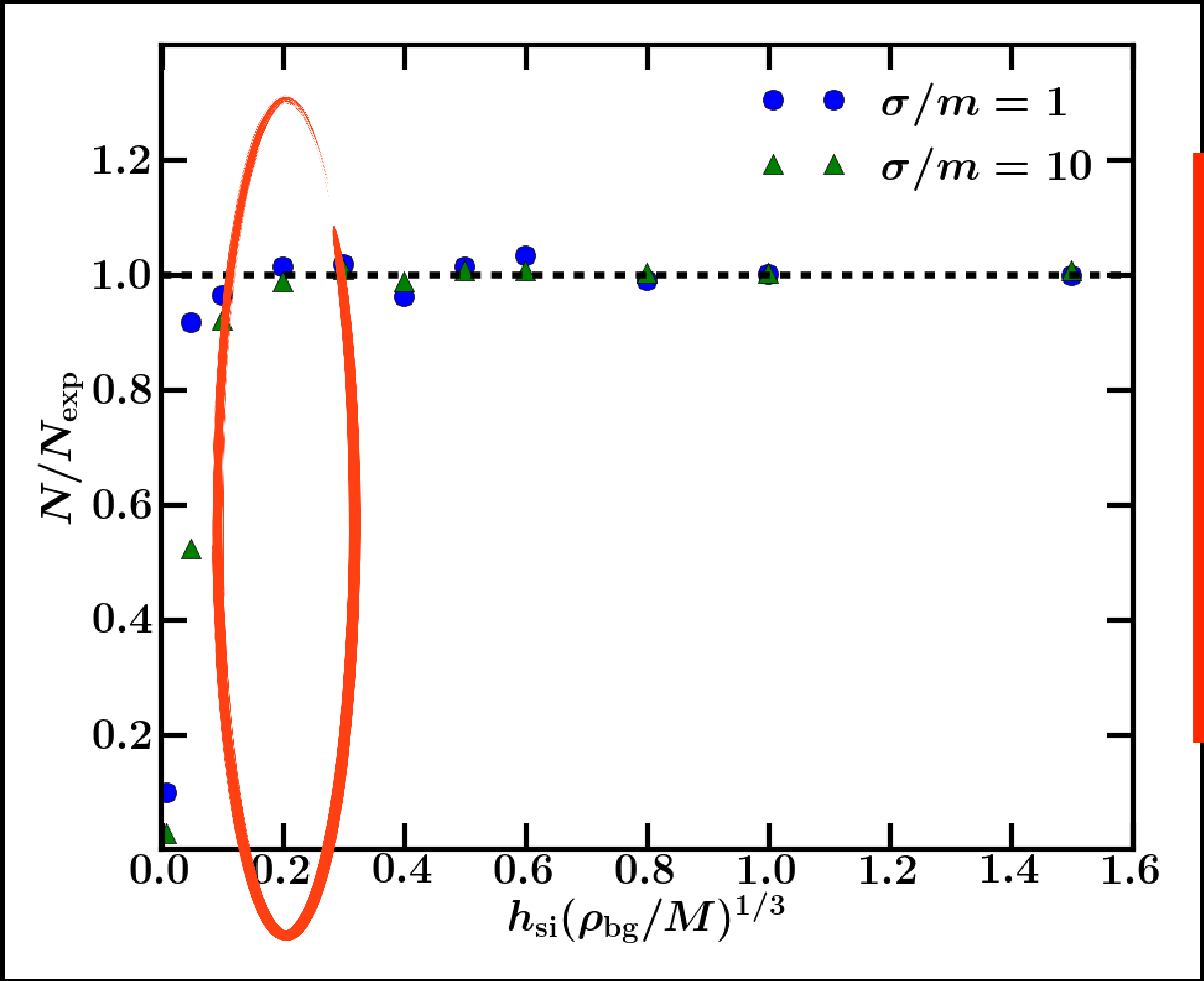

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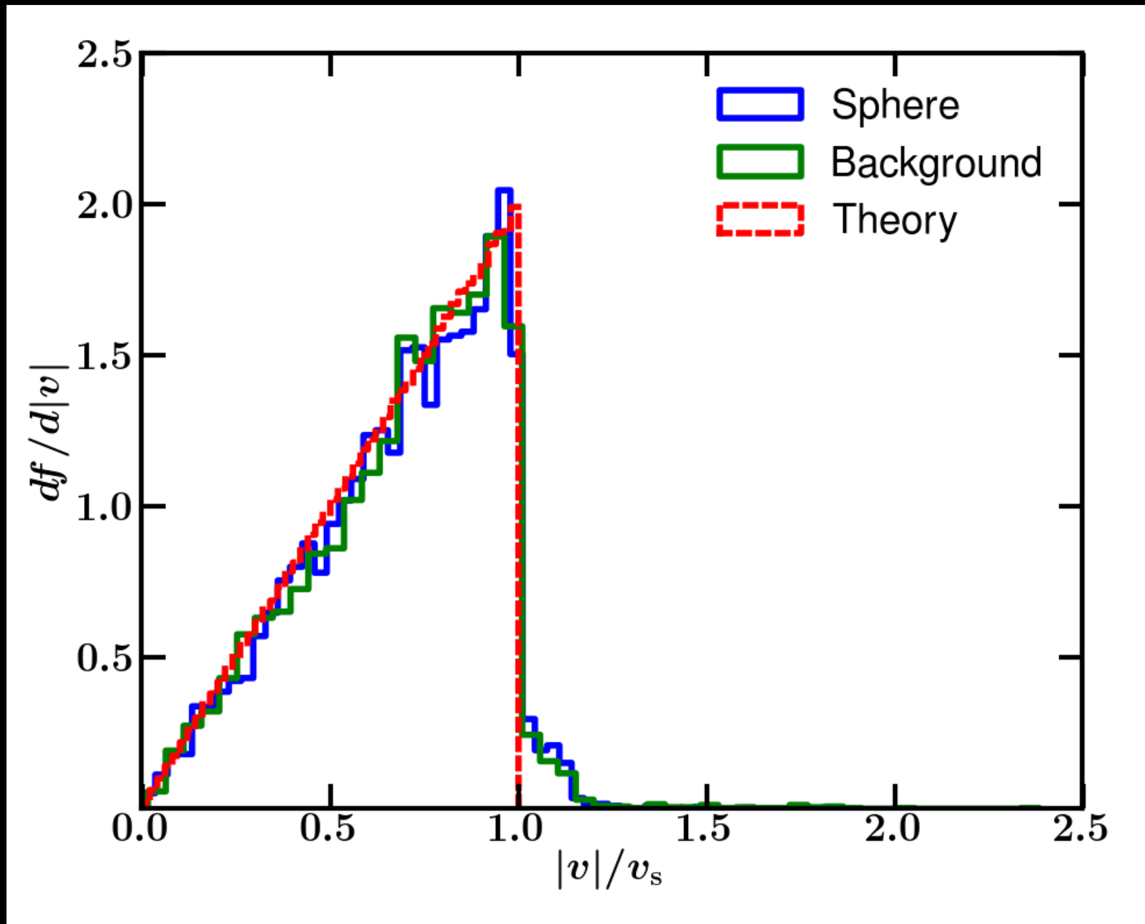
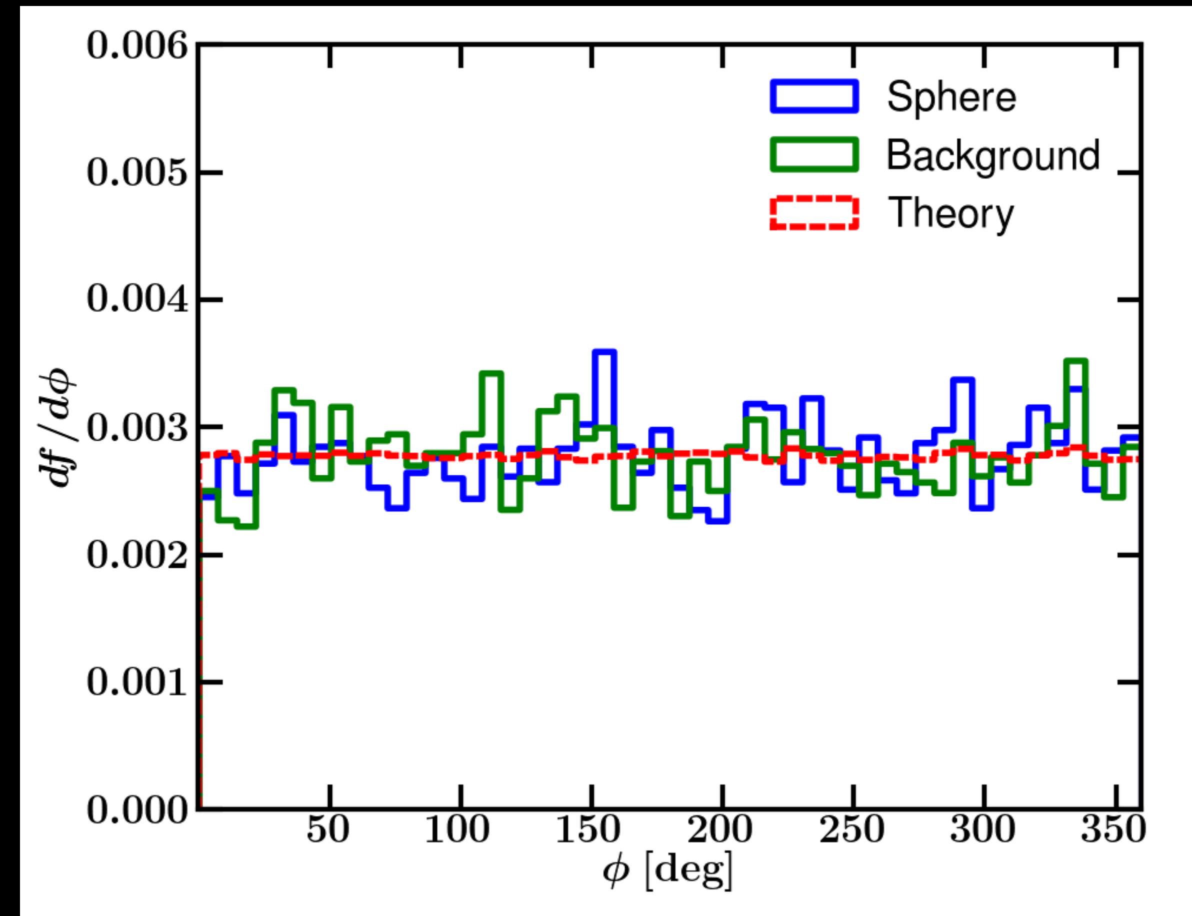
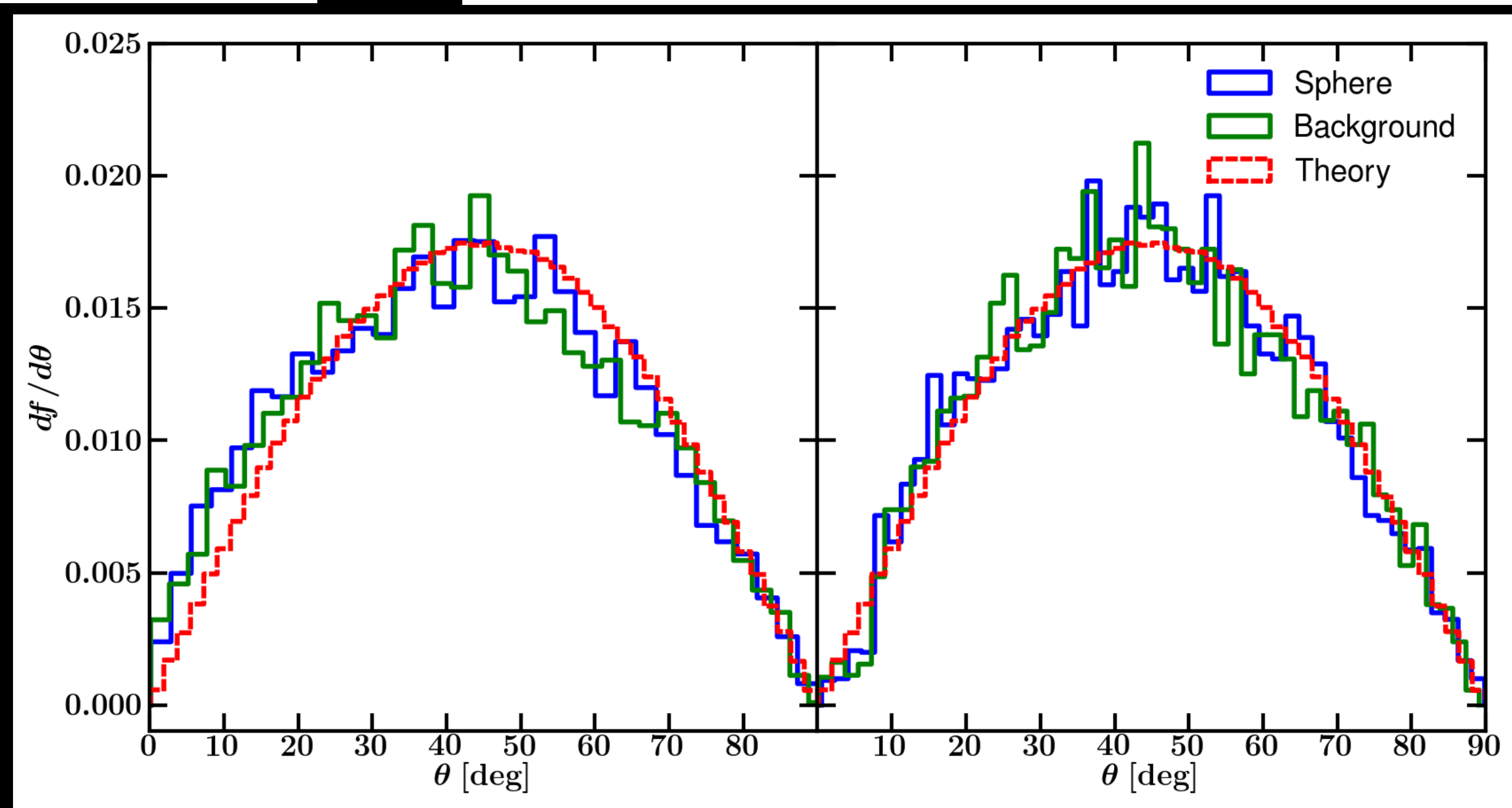
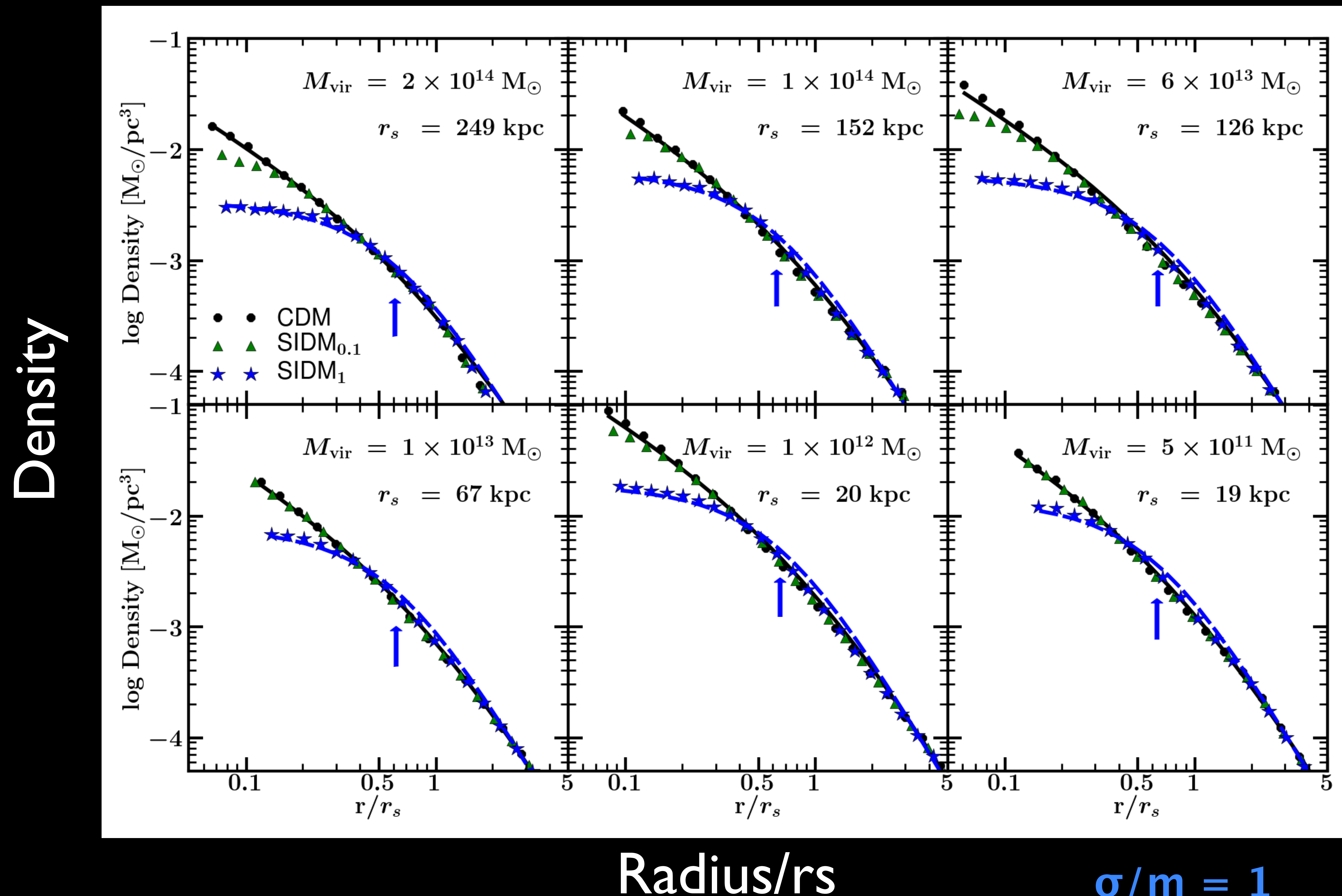




Correct post-scatter kinematics



Results from cosmological simulations - Halo densities



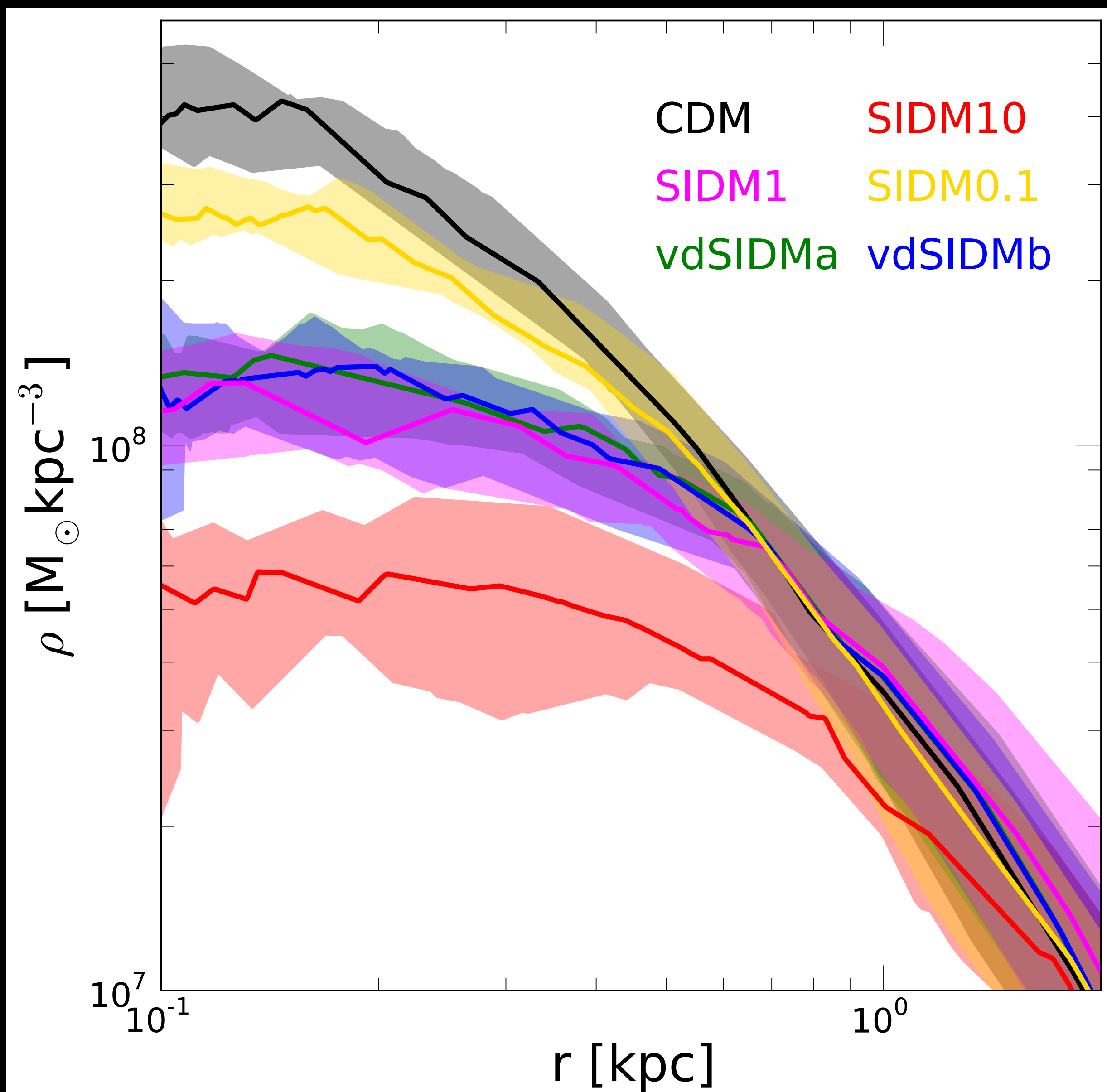
$\sigma/m = 1$

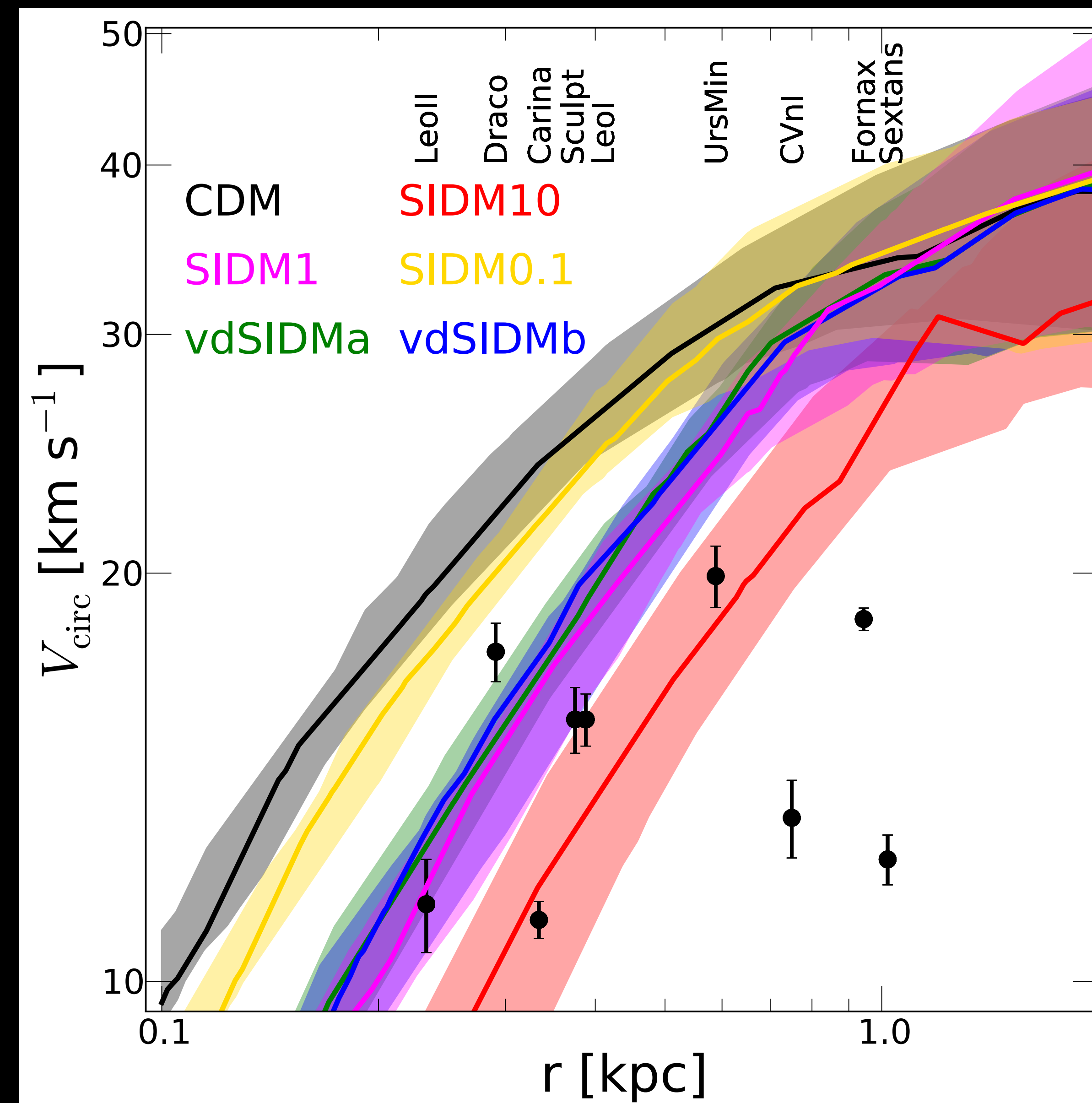
$\sigma/m = 0.1$

Rocha et al. 2013
Peter et al. 2013

Constraints from: core sizes & densities

Predictions vs. Observations





Zavala, Vogelsberger and Walker 2012

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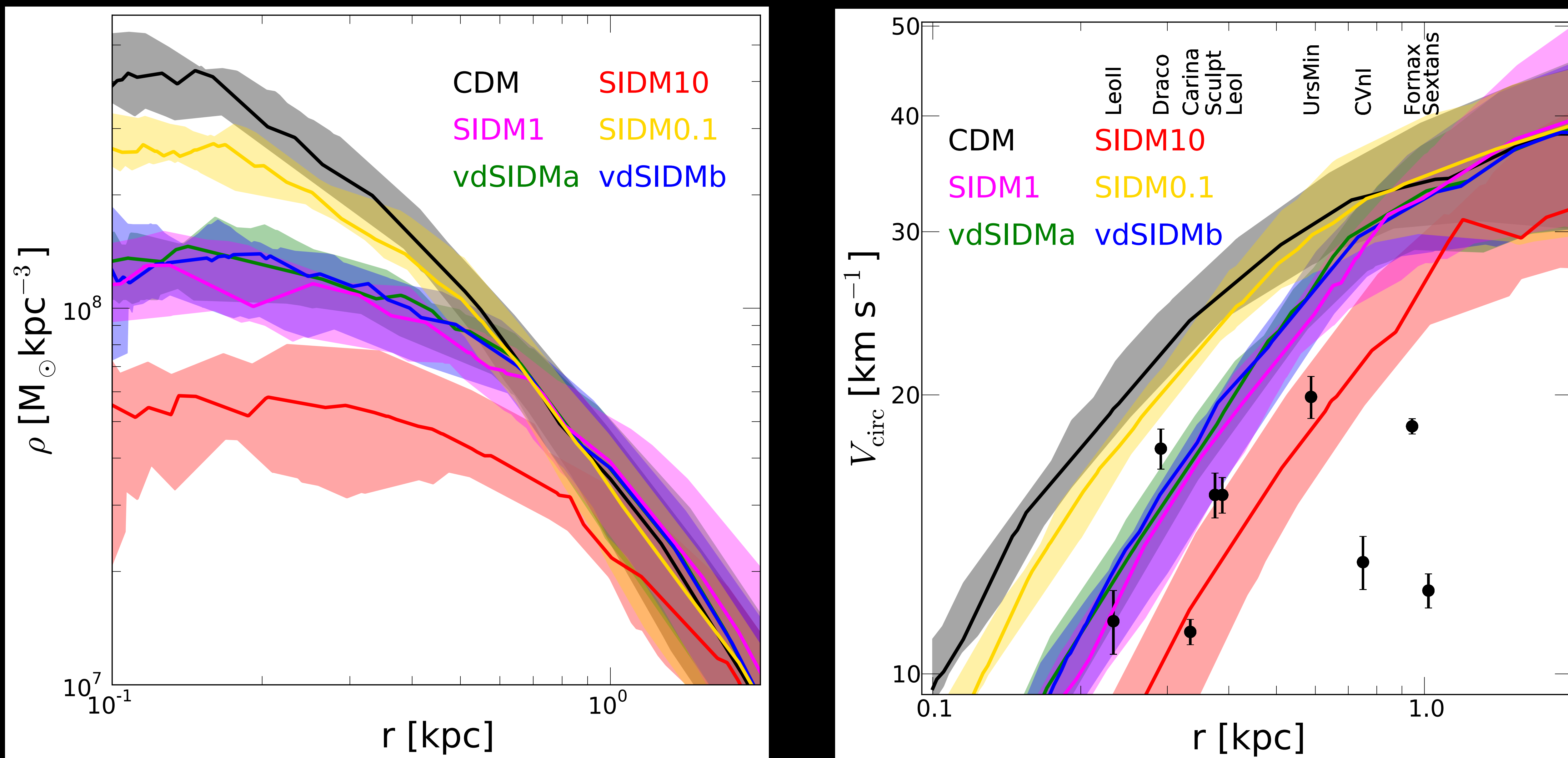
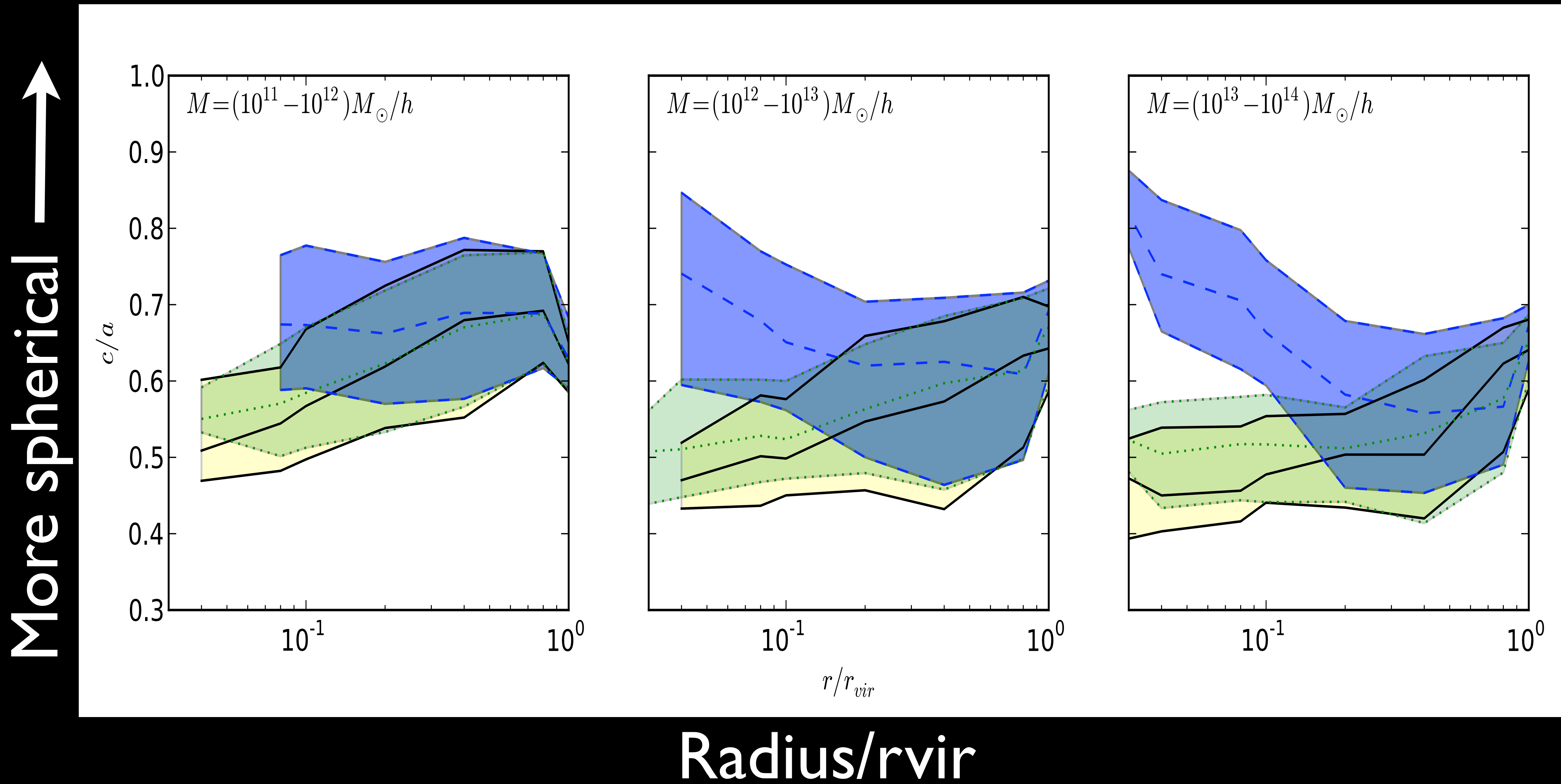


σ/m~0.6 cm^2/g seems to work!!

Zavala, Vogelsberger and Walker 2012

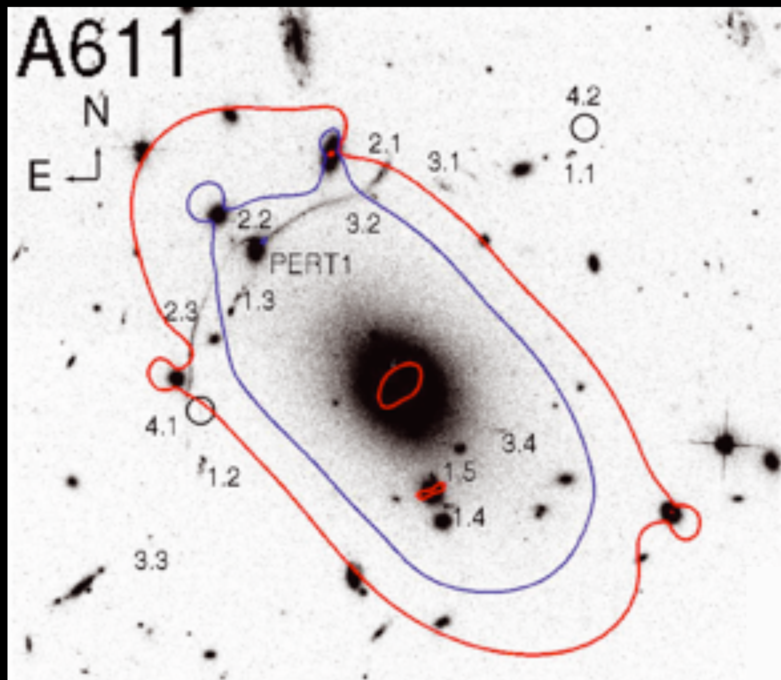
Results from cosmological simulations - Halo shapes



$\sigma/m = 1\ cm^2/g$
$\sigma/m = 0.1\ cm^2/g$
collisionless

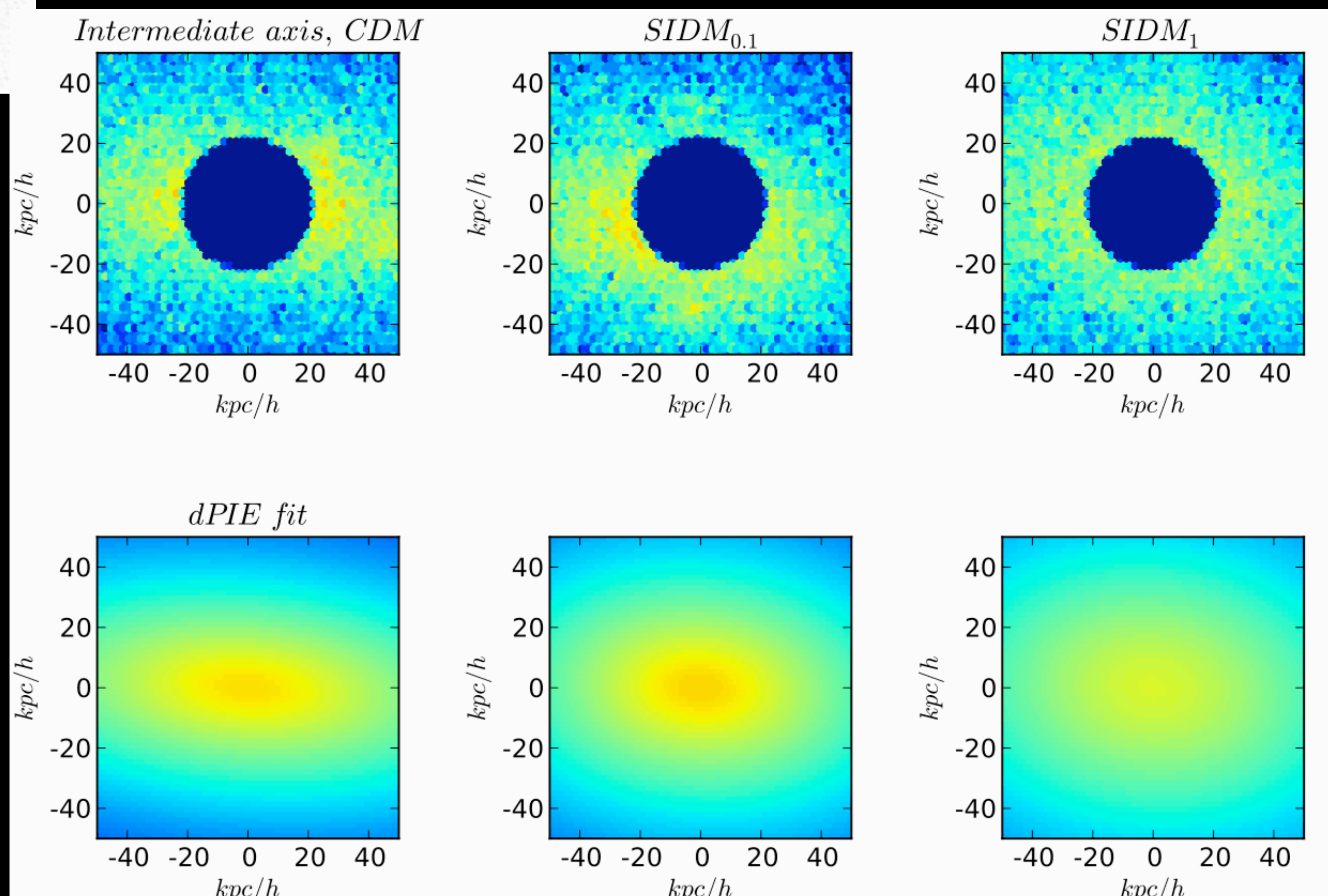
Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo shapes



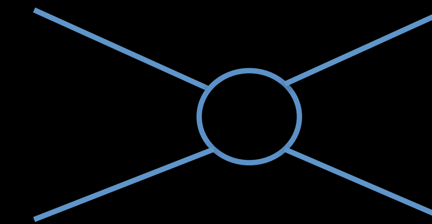
From LoCuSS sample
Richard+ 2010

We see surface density (or gravitational potentials) in projection.

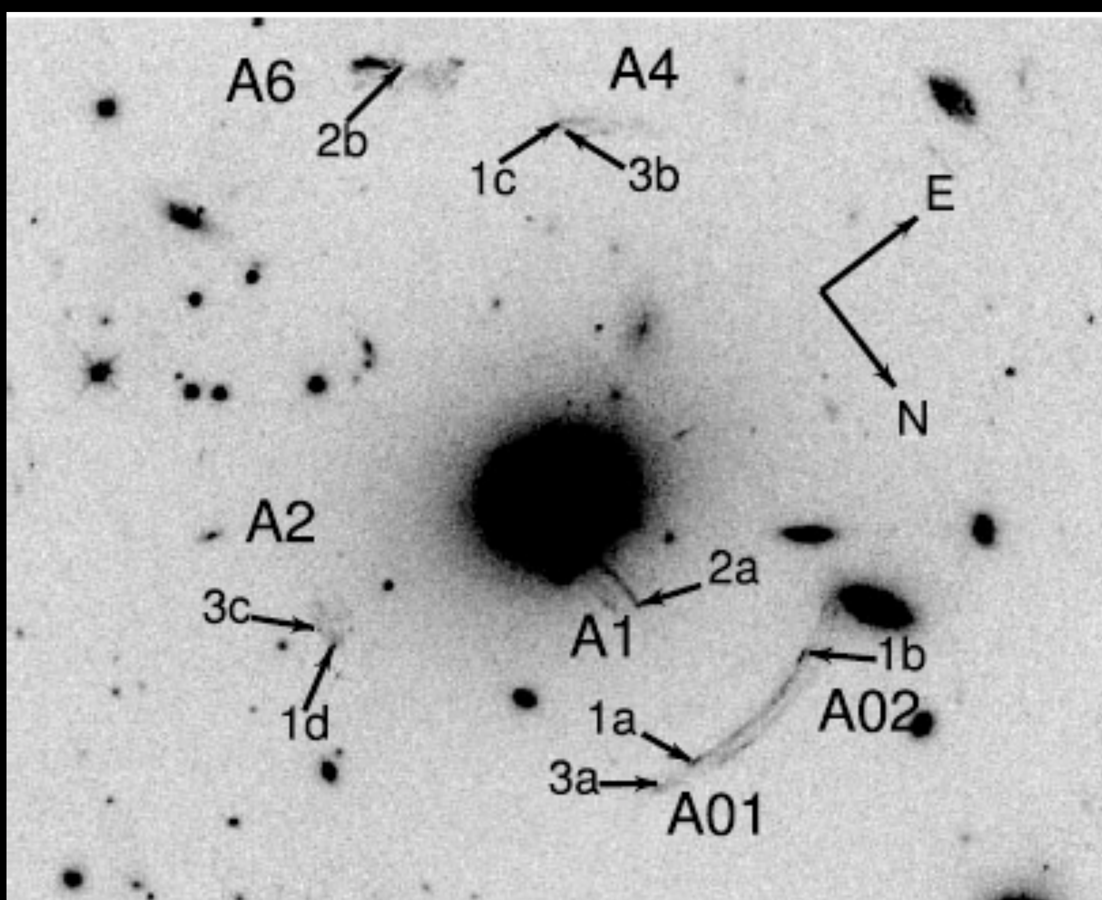


Rocha et al. 2013
Peter et al. 2013

The TKO of SIDM



Miralda-Escude (2002)



MS 2137-23
Sand et al. 2008

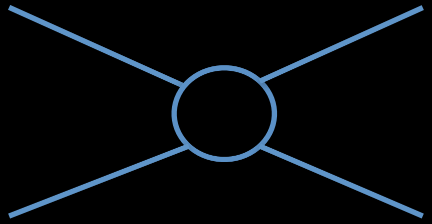
Requires a non-circularly-symmetric surface density at r > 70 kpc.

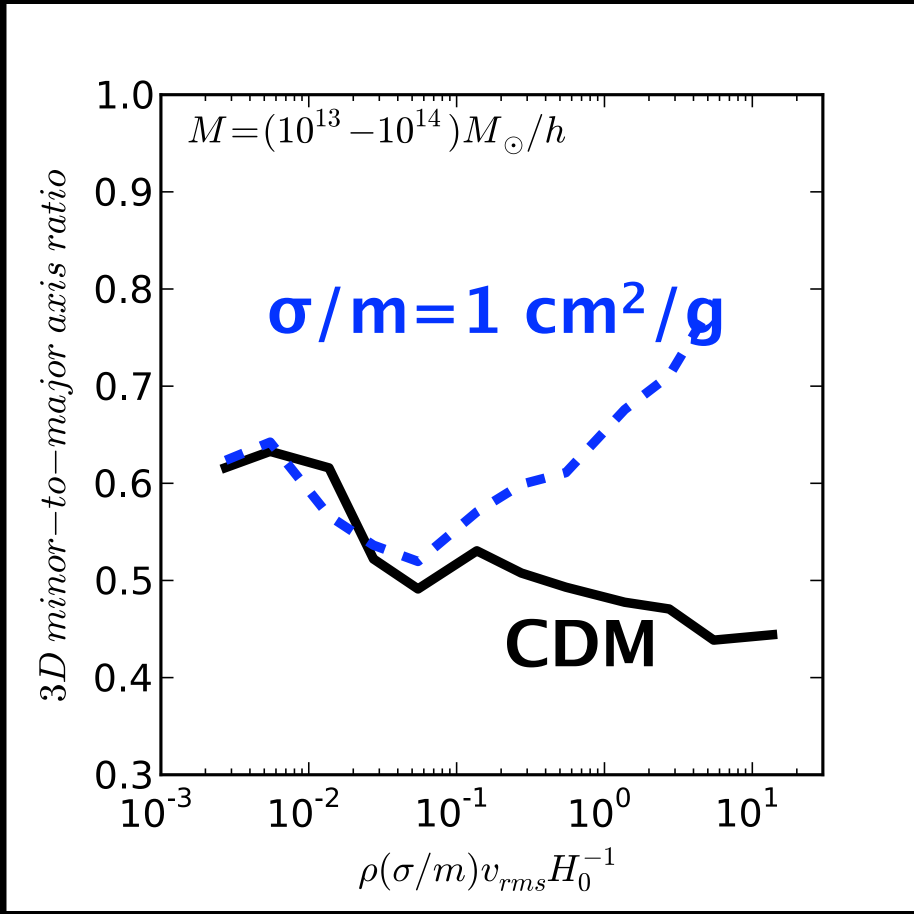
Assume ε=0 if $\Gamma/H_0 \gtrsim 1$

➔ σ/m < 0.02 cm^2/g.

Tightest constraint by far (by > 10x)!

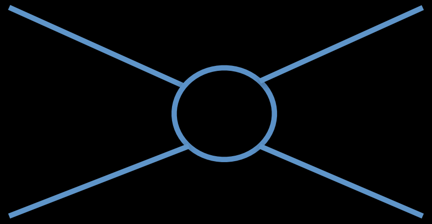
The problem with shapes

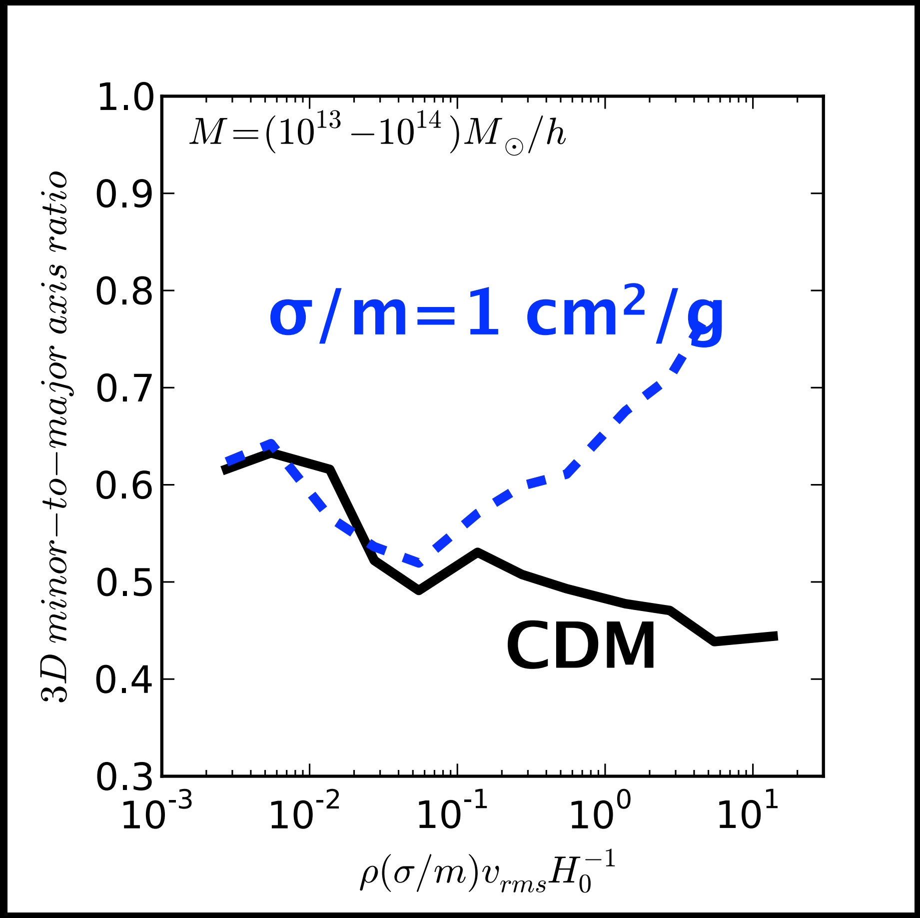




- We see surface density (or gravitational potentials) in projection.
- If inner parts have flattened density, outer parts have even greater weight.

The problem with shapes





$$\Gamma/H_0 \gg 10$$

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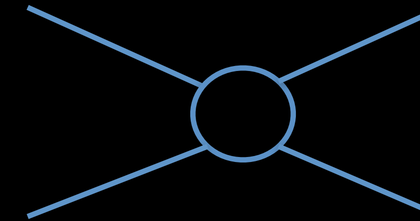

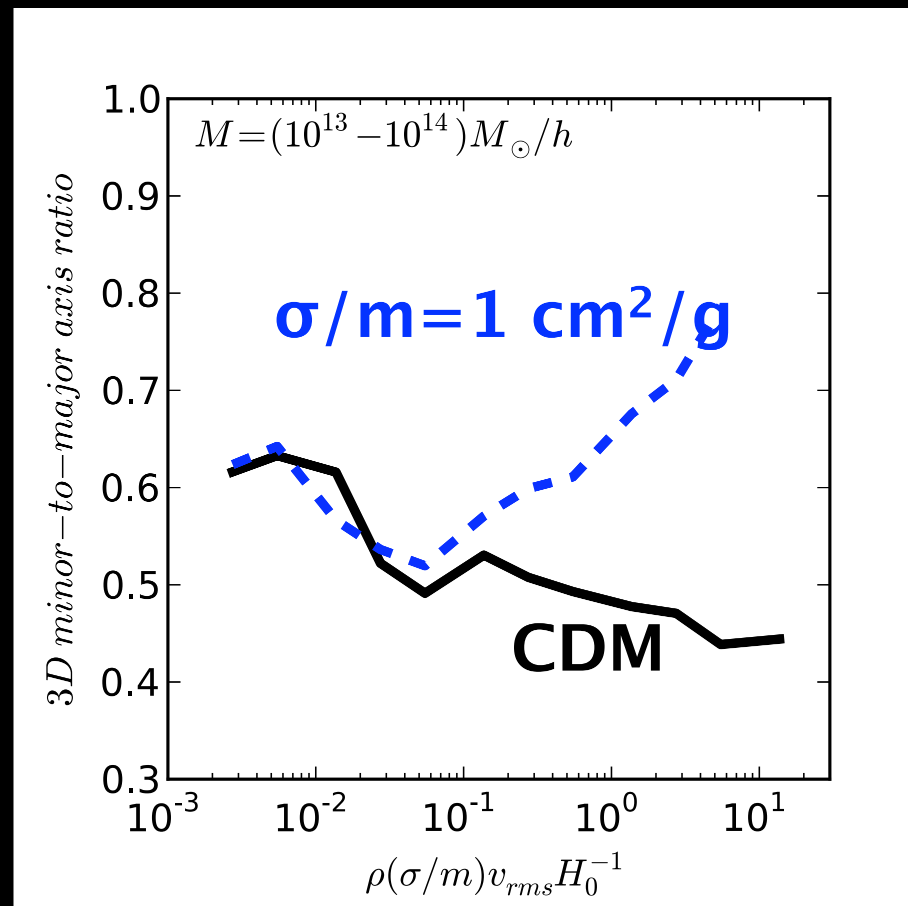

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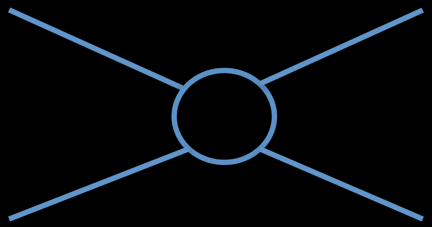

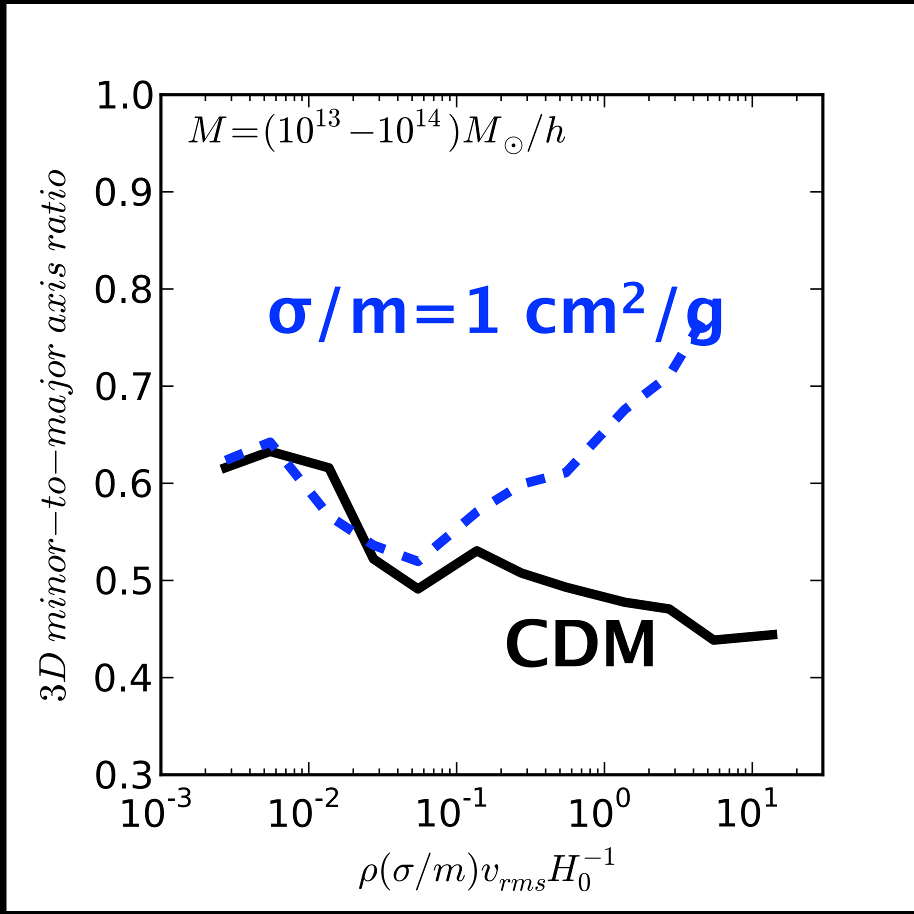

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Previous Constraints

Reference	Constraint [cm^2 /g]	From	Problem
Yoshidal et. al 2000	$\sigma/m < \sim 0.1$	Cluster density core	One cluster
Dave et. al 2001	$\sigma/m = 0.1 - 10$	Dwarfs density Cores	Narrow mass range
Gnedin & Ostriker 2001	$\sigma/m < 0.3$	Subhalo evaporation	Overestimated subhalo evaporation
Miralda-Escude 2002	$\sigma/m < 0.02$	Halo shapes	Overestimated halo sphericity
Randall et al. 2008	$\sigma/m < 0.7 - 1.25$	Bullet Cluster	High central densities and relative vel.

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Vogelsberger et al.2012 Zavala et al. 2012	$\sigma/m > 0.1$ Velocity dependence may be needed	MW dwarfs solves TBTF	MW dwarfs only (resolution?)
MCC	**Expect best constraints stay tuned!!**	Merging Clusters	**Time will tell**

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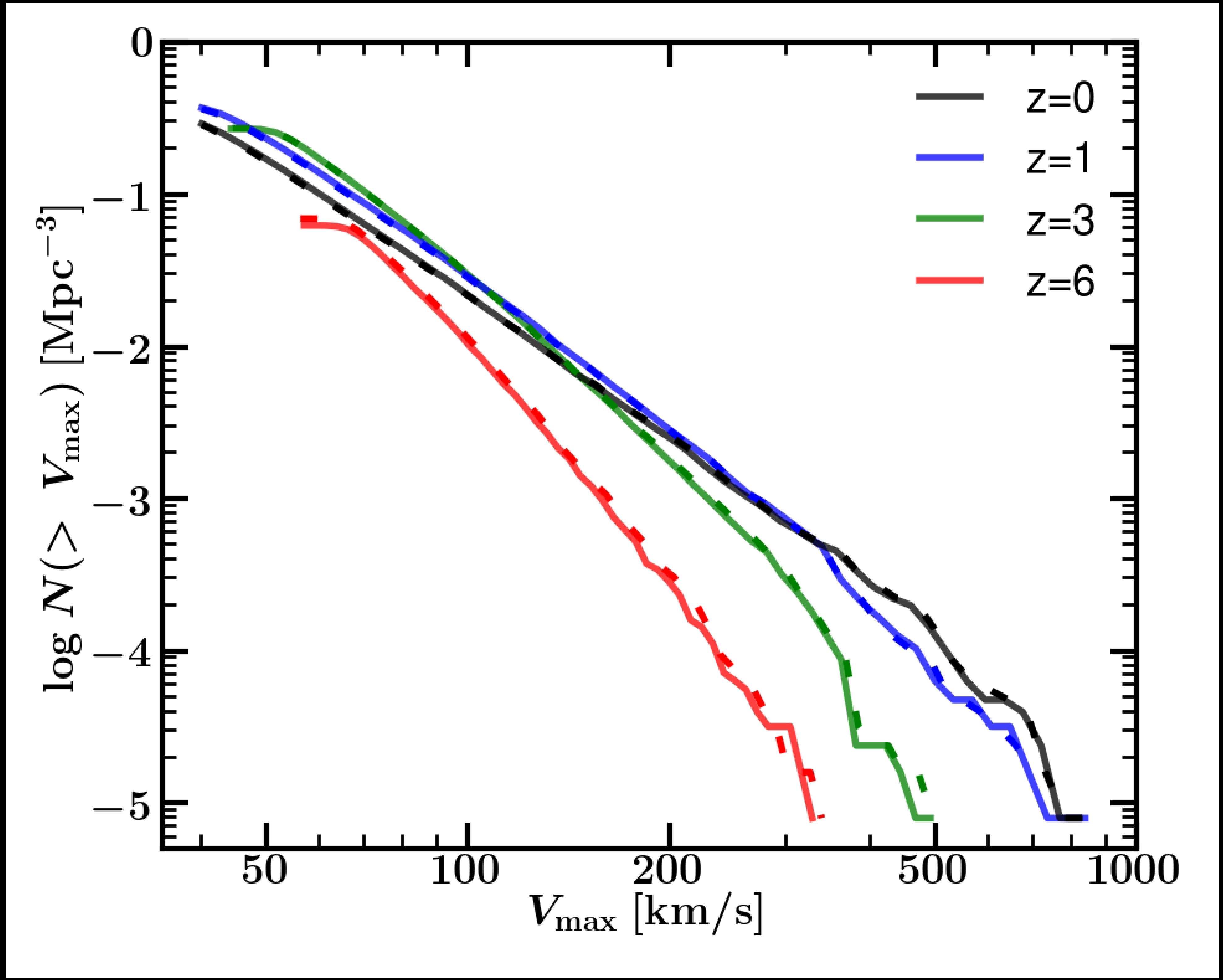
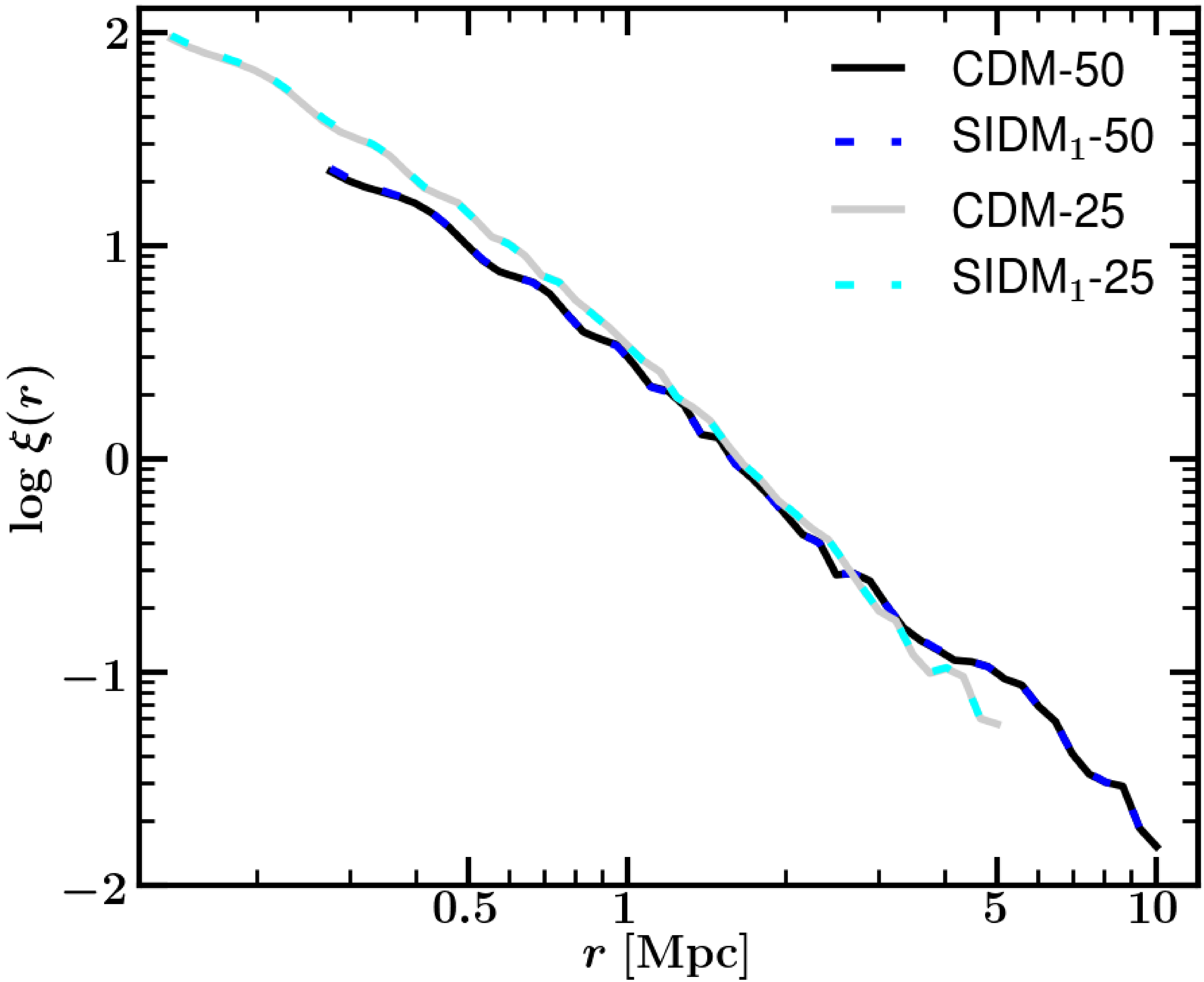
Dave et. al 2001	$\sigma/m = 0.1-\cancel{10}$	Dwarfs cores	Narrow mass range
Randall et al. 2008	$\sigma/m < 0.7-\cancel{1.}25$	Bullet Cluster	High central densities and relative vel.
Vogelsberger et al.2012 Zavala et al. 2012	$\sigma/m > 0.1$ Velocity dependence may be needed	MW dwarfs solves TBTF	MW dwarfs only (resolution?)
MCC	**Expect best constraints stay tuned!!**	Merging Clusters	**Time will tell**

For Gev particles these are equivalent to strong force interactions (nucleon–nucleon scattering)!!

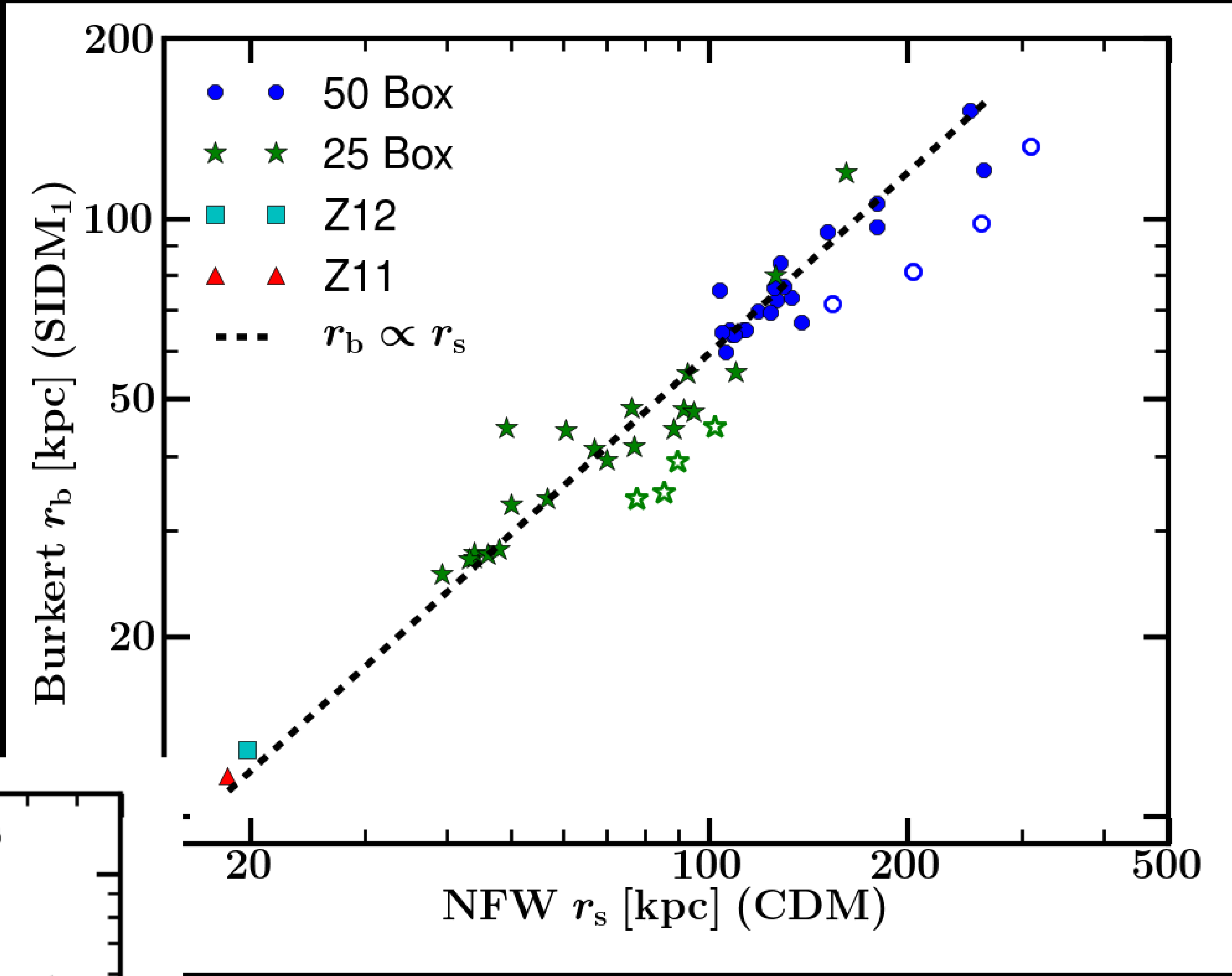
Identical Abundance of Halos

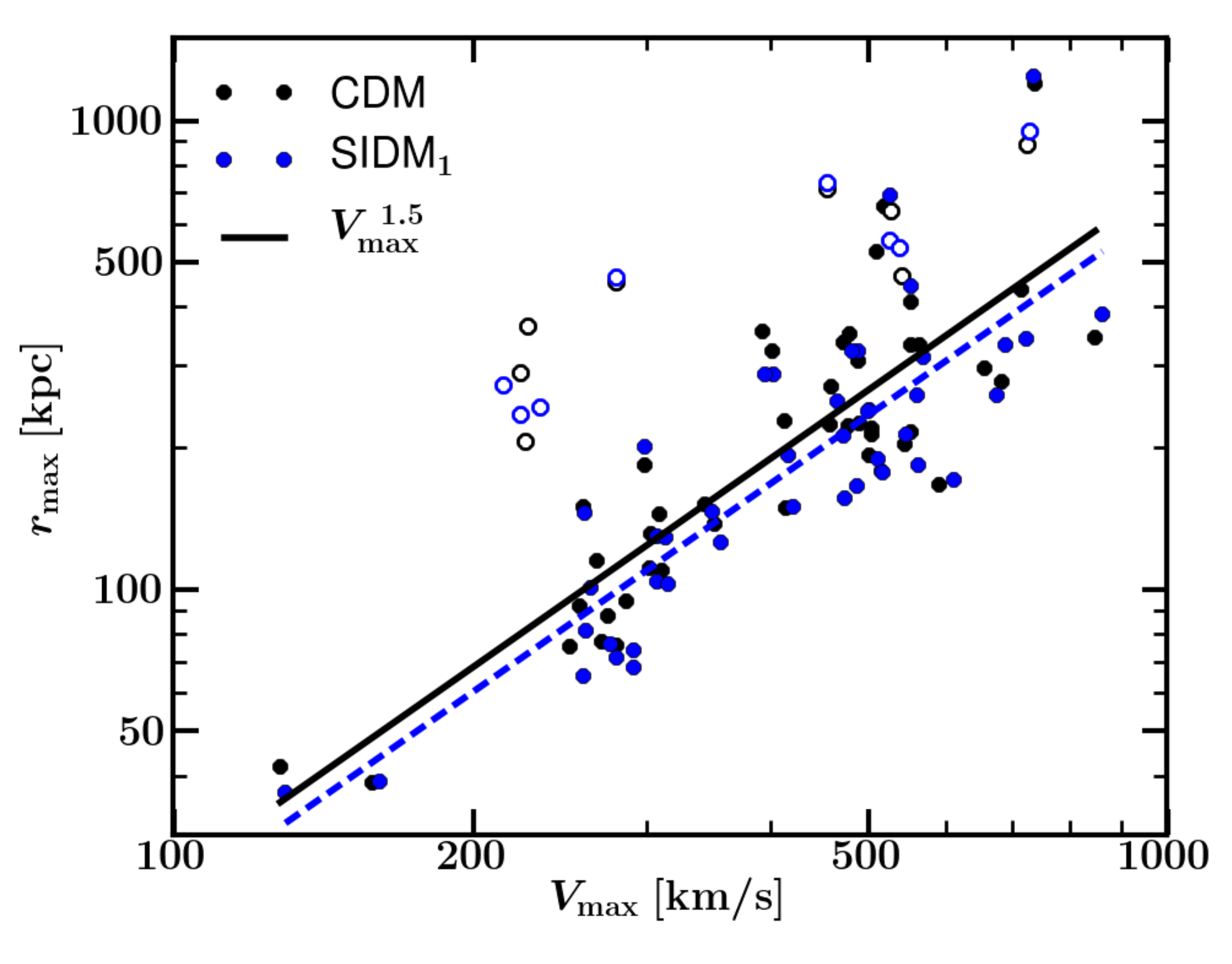



CDM-50
$SIDM_1$-50
CDM-25
$SIDM_1$-25
2
1
0
−1
−2
$\log \xi(r)$
0.5
1
5
10
r [Mpc]

σ/m = 1 cm^2 /g

rb/rs ~ 1





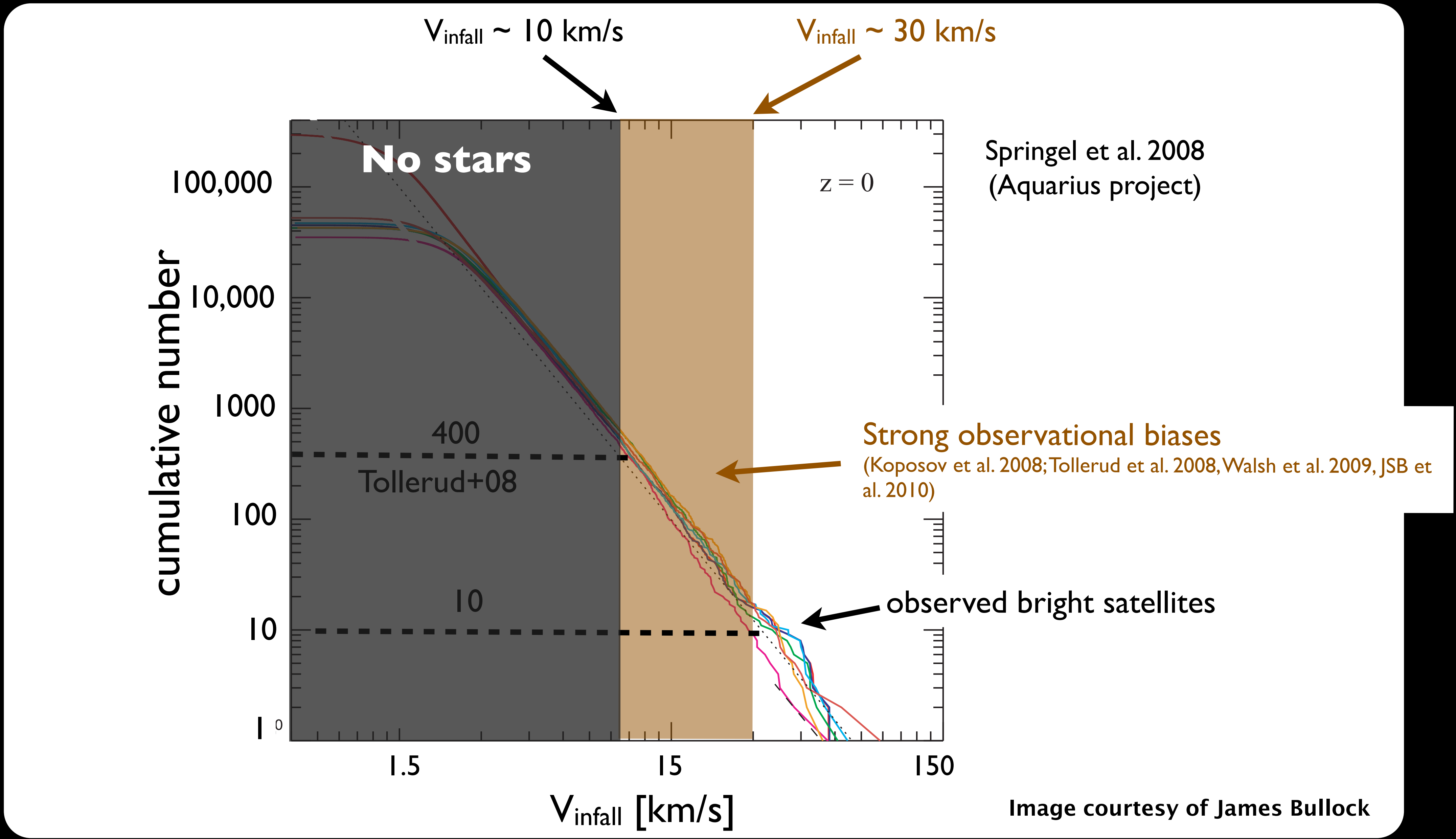
- Vmax/Rmax similar to CDM
- Vmax-Rmax relation unchanged

Rocha et al. 2012
arXiv:1208.3025

Table 1: Simulations discussed in this paper.

Name	Volume $L_{\rm Box}$ [h^{-1} Mpc]	Number of Particles $N_{\rm p}$	Particle Mass $m_{\rm p}$ [h^{-1} M$_\odot$]	Force Softening ϵ [h^{-1} kpc]	Smoothing Length $h_{\rm si}$ [h^{-1} kpc]	Cross-section σ/m [cm^2/g]
CDM-50	50	512^3	6.88×10^7	1.0	–	0
CDM-25	25	512^3	8.59×10^6	0.4	–	0
CDM-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	–	0
CDM-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	–	0
SIDM$_{0.1}$-50	50	512^3	6.88×10^7	1.0	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-25	25	512^3	8.59×10^6	0.4	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	$1.4\,\epsilon$	0.1
SIDM$_1$-50	50	512^3	6.88×10^7	1.0	$2.8\,\epsilon$	1
SIDM$_1$-25	25	512^3	8.59×10^6	0.4	$2.8\,\epsilon$	1
SIDM$_1$-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	$2.8\,\epsilon$	1
SIDM$_1$-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	$1.4\,\epsilon$	1

Summary of Controversies with the Standard Model of Structure Formation



- **Missing satellites**: persists to today, at some level. May be explained by reionization suppression + inefficient galaxy formation